CLIMATE PROFILE FOR THE CITY OF FLAGSTAFF

Climate Profile for
The City of Flagstaff, Arizona

Climate Assessment for the Southwest (CLIMAS)
University of Arizona

March 20, 2018

Alison M. Meadow
CLIMAS and Institute of the Environment

Sarah LeRoy
CLIMAS and Institute of the Environment

Jeremy Weiss
CLIMAS and School of Natural Resources and the Environment

Ladd Keith
CLIMAS and College of Architecture, Planning, and Landscape Architecture

Table of Contents

Executive Summary

The earth's climate is changing. Global average temperatures have risen 1.8° F since 1901 (Wuebbles et al. 2017). Warming temperatures are driving other environmental changes such as melting glaciers, rising sea levels, changes in precipitation patterns, and increased drought and wildfires.

The magnitude of future changes will depend on the amount of greenhouse gases (GHGs) (particularly carbon dioxide) emitted into our atmosphere. Without significant reductions in GHGs, global average temperatures could rise as much as 9° F over pre-industrial temperatures by the end of this century. Even with drastic reductions in emissions, we could limit the warming to 3.6° F or less (Wuebbles et al. 2017).

Coconino County has been experiencing climate changes as well. Average temperatures have been rising, particularly in the last 30 years. The region is likely to see fewer cold days and more hot days in the coming decades. And annual average temperatures could rise even more than the global average–possibly more than 10° F higher than the long-term average in the region.

Projections of future climate for Coconino County include:

<u>Temperature</u>

- Average temperatures in Coconino County have been rising since about the mid-1980s. Almost all years since 1985 have had average annual temperatures above the long-term average.
- Minimum temperatures, which manifest as days not being as cold and as fewer cold days per year, are largely driving the upward trend in temperatures.
- These trends are projected to continue into the future. Scenarios for Coconino County indicate that average temperatures could be 5° F above the current average (52.3° F) by 2050 and more than 10° F above the current average by the year 2100.

<u>Precipitation</u>

- Precipitation has historically been variable, as is normal for this region. There is no clear trend toward changes in average precipitation amounts in Coconino County.
- The same variability is present in future projections of precipitation with no clear indication about changes in overall average amounts.
- Rising temperatures will, however, increase evaporation and transpiration rates, which will lead to drier soils and contribute to more frequent and severe drought.
- Rising low temperatures also indicate a likely change from precipitation falling as snow to more of the precipitation falling as rain during colder months of the year.

Extreme Temperatures

- From 1950–2017, the average number of days above 90° F in Flagstaff was 2 days per year. The projected change in the number of days above 90° F is as high as 80 days per year by the end of this century.
- On average, Flagstaff has experienced 197 days per year in which minimum temperatures drop below freezing (32° F). By the year 2100, Flagstaff could experience as few as 100 days that reach freezing temperatures.

Based on this examination of Flagstaff and Coconino County's historic and projected climate, we see a clear warming trend. Although natural variability will always exist, meaning some years will be warmer and some colder, the overall trend is toward warmer temperatures; in particular, low temperatures are not, and will not be, as low as in the past. Although there are no clear trends in precipitation, the warmer temperatures will contribute to an overall drying trend.

The implications of these changes for Flagstaff will be discussed in climate vulnerability assessment process, which will be completed in the spring of 2018.

Introduction to the Climate Profile

Decisions that require the use of climate and weather information, such as how to best manage natural resources or help your community adapt to a changing climate, often need long-term records–or data–about daily ***weather***[1]. Weather data in its most basic form is made up of measurements of temperature and precipitation taken at least once a day. When collected at the same locations for a long time, weather data gives us a lot of information about the ***climate*** of a place. For example, by looking at many years of weather data we can see how prone a region is to droughts, floods, heat waves or cold spells. These historical weather records also reveal ***climate trends***, such as whether a place is getting wetter or drier or warmer or cooler over long periods of time.

Projections of future climate conditions, commonly referred to as ***climate projections***, are developed using computer-based climate models. These models provide us with estimates or scenarios of possible future climate conditions.

All of this information, both observed (historical) data and projected data, can be useful in helping a community make decisions about natural resources or economic development opportunities. This climate profile has been created for Coconino County (which includes Flagstaff) using observed climate and weather data as well as computer model projections of future climate. The information is presented for all of Coconino County because the area is small enough to be relevant to the City of Flagstaff and large enough for the analyses (particularly the projected future climate scenarios) to be robust. Analysis of both sets of data reveal several trends that can help the City of Flagstaff plan for its future.

[1] ***Bold/italicized*** terms are defined in the Glossary at the end of the report.

Climate Trends and Climate Change

Global average temperatures are rising. They do not rise everywhere or every year in exactly the same amount. Natural climate variability means that some years are still cold or colder than average. But overall, the whole world is warming up.

Figure 1 shows some of the changes scientists and others have observed about the ways in which the Earth is changing. The white arrows indicate upward trends, like rising temperatures and sea levels. The black arrows indicate downward trends, such as the amount of snow in northern and mountain regions.

Ten Indicators of a Warming World

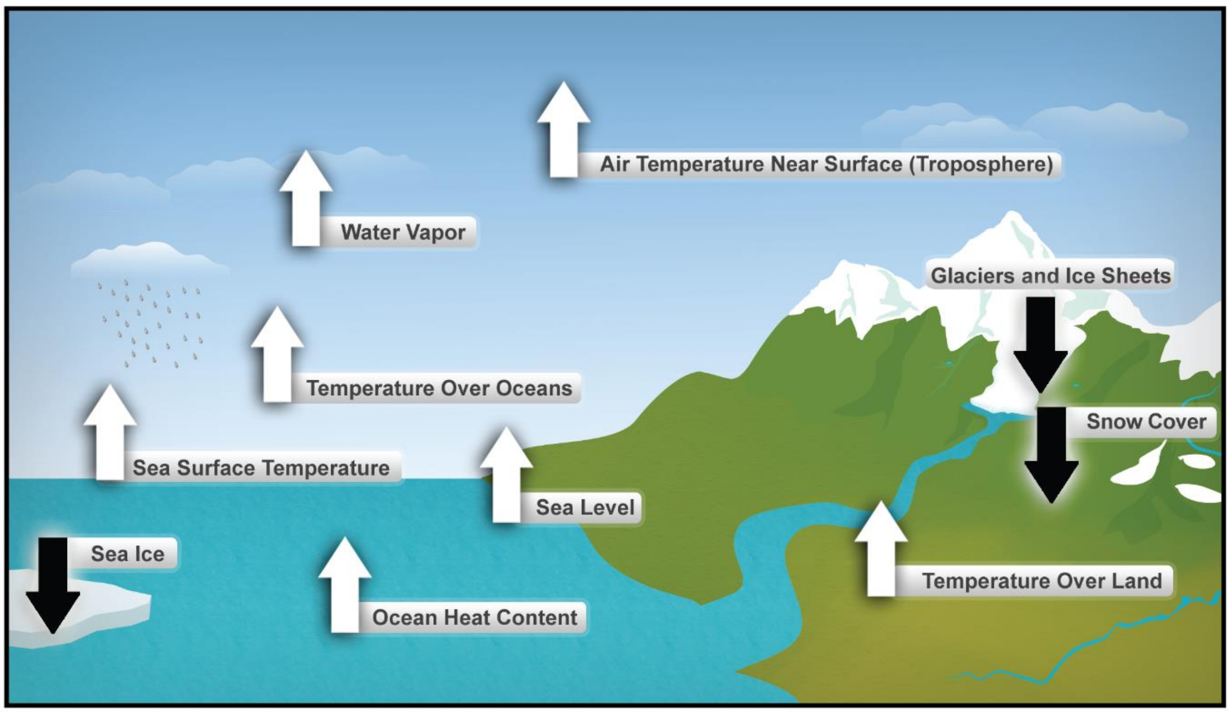

Figure 1: Observed indicators of a warming world. White arrows indicate increasing trends. Black arrows indicate decreasing trends. Source: http://nca2014.globalchange.gov/report/our-changing-climate/observed-change#tab2-images.

While most areas of the United States have warmed in recent decades, not every area has experienced (or will experience) a constant rate of warming (Figure 2).[2] **The Southwest is one of the regions that has experienced warming above 1.5° F in recent decades**. The warming is even clearer during the winter season.

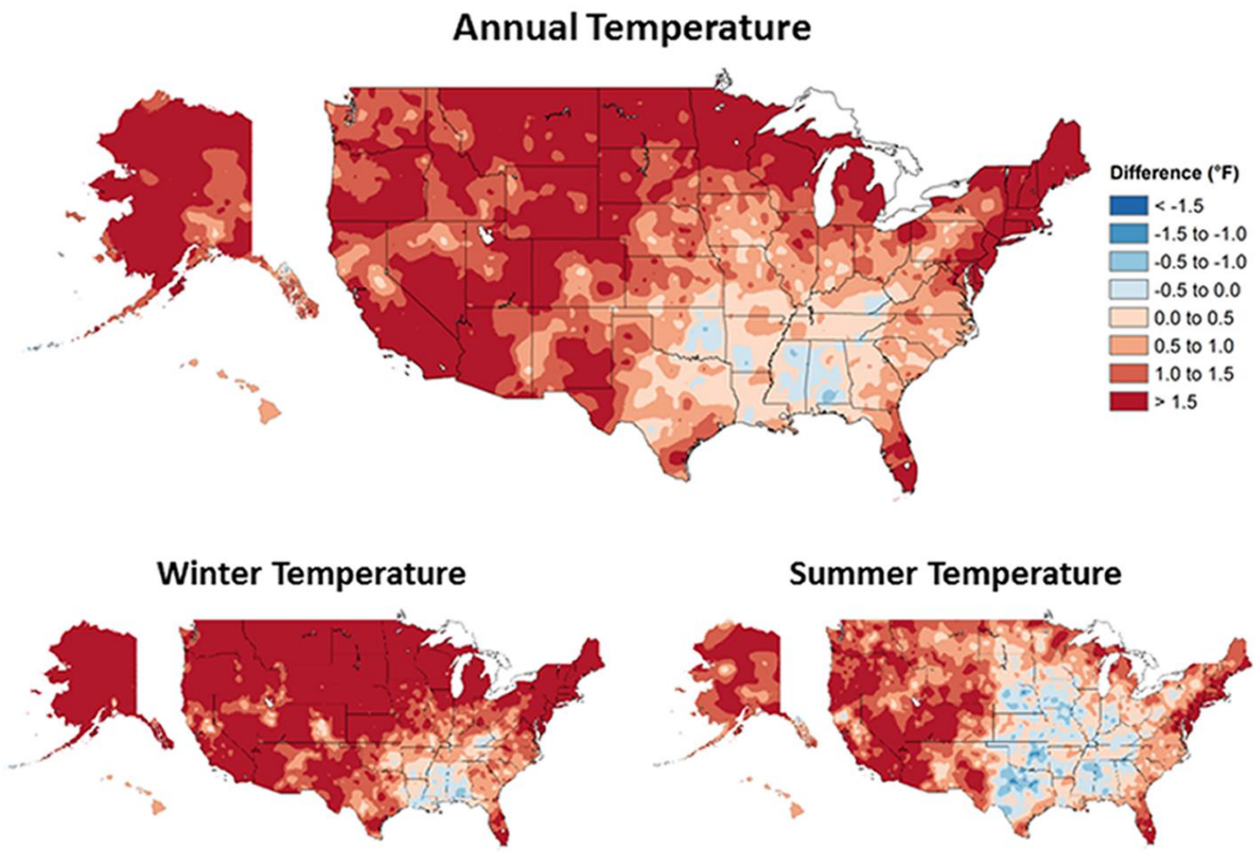

Figure 2: Observed temperature changes in the U.S. comparing the current period (1986–2016) to the period 1901–1960. The darker the color, the greater the difference between 1901–1960 and 1986 - 2016. Source: Climate Science Special Report: https://science2017.globalchange.gov/.

[2] In the southeastern United States are several areas that appear to have cooled instead of warmed. Researchers have linked this period of cooling to a combination of factors including: thick clouds, which decrease the amount of sunlight reaching the land surface; unusually high soil moisture, which contributes to high evaporation rates; and lower daytime temperatures in those areas (Kennedy 2014); sea-surface temperatures in the central Pacific Ocean, which affect storm patterns (Meehl, Arblaster, and Chung 2015); and air pollution from aerosols that scatter or reflect sunlight (Leibensperger et al. 2012). This pattern, sometimes called the “warming hole” (i.e., a hole in the warming trend) has reversed since the year 2000 and the southeastern United States is now warming at a rate similar to surrounding regions (Meehl, Arblaster, and Chung 2015).

Why is the climate changing?

The sun's energy enters the Earth as short wave radiation. The Earth and its atmosphere reflect some of this energy back to space, while some of it naturally passes through the atmosphere and is absorbed by the Earth's surface (Figure 3). This absorbed energy warms the Earth's surface, and is then re-radiated back out to space as long wave radiation. However, some of the long wave radiation doesn't make it to space, and is absorbed in the atmosphere by ***greenhouse gases (GHGs)***, warming the surface and keeping the planet warmer than it would be without an atmosphere. This natural process is what makes the earth habitable. However, while GHGs are naturally occurring in the atmosphere, human activity is increasing the amounts of GHGs emitted directly to the atmosphere. Carbon dioxide, methane, and nitrous oxide are major GHGs. Carbon dioxide (CO_2) is released through the burning of fossil fuels such as coal, natural gas, and gasoline, and accounts for about 75% of the warming impact of these emissions. Methane (from such sources as livestock, fossil fuel extraction, and landfills) accounts for about 14% of the warming impact from GHG emissions, and has a much more potent effect on global warming per unit of gas released. Agriculture contributes nitrous oxide to the atmosphere from fertilizers and livestock waste; it is the most potent GHG and accounts for about 8% of the warming.

By increasing levels of GHGs, humans are intensifying the natural effect of warming the planet. Heat from the sun can still get in, but more and more of it cannot get back out again.

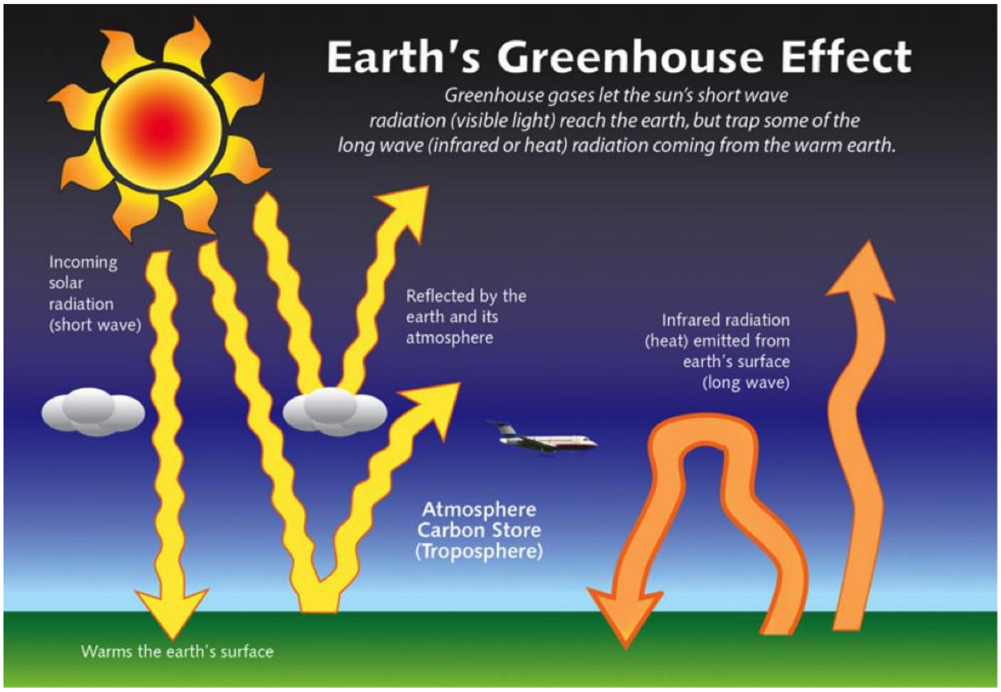

Figure 3: The Greenhouse Effect. Source: New York State *Department of Environmental Conservation;* http://www.dec.ny.gov/energy/76533.html

By comparing the amount of carbon dioxide in the atmosphere to changes in temperatures, we can see that the rising global temperatures are correlated to rising carbon dioxide concentrations in the atmosphere (Figure 4). In Figure 4, the blue bars represent years with an average temperature lower than the long-term global average of 57° F and the red bars are years in which the temperature was warmer than average. The black line traces the amount of carbon dioxide in the atmosphere (in parts per million, or ppm).

Although we see a long-term trend toward higher temperatures, there are still year-to-year variations in temperature that are due to natural processes such as the effects of the El Niño Southern Oscillation (ENSO), a shift in global atmospheric circulation patterns), which can cause global temperatures to quickly rise during El Niño years and cool during La Niña years.

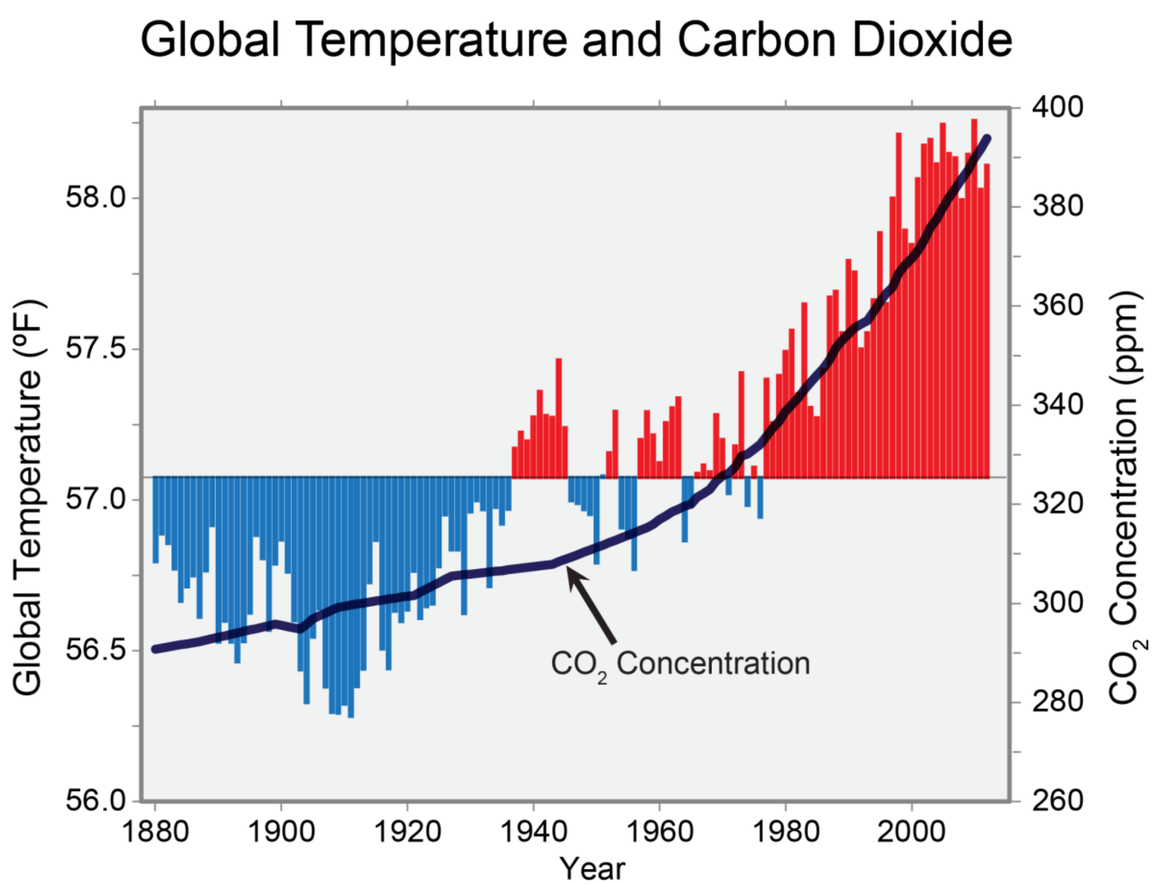

Figure 4: The corresponding rise in CO_2 and global temperatures. Source: http://nca2014.globalchange.gov/report/our-changing-climate/observed-change#tab2-images

The strong relationship between temperature and amount of carbon dioxide is apparent, and scientists have been able to perform more detailed experiments to confirm that the increasing amounts of GHGs are the cause of the warming. Since a controlled experiment cannot be conducted in the real world by raising and lowering overall GHGs, scientists build mathematical models of the Earth's systems using computers. The graph in Figure 5 shows results of an experiment with climate models in which scientists compared natural warming factors such as periodic changes in how much energy the Earth receives from the sun and volcanic eruptions with the temperatures that had been observed since 1895. They found that the natural warming factors (the green shaded area) do not match up with the observed temperatures. But when they added in human causes–GHG emissions–along with natural processes (the blue shaded area) they found that their results matched very well with the observed temperatures.

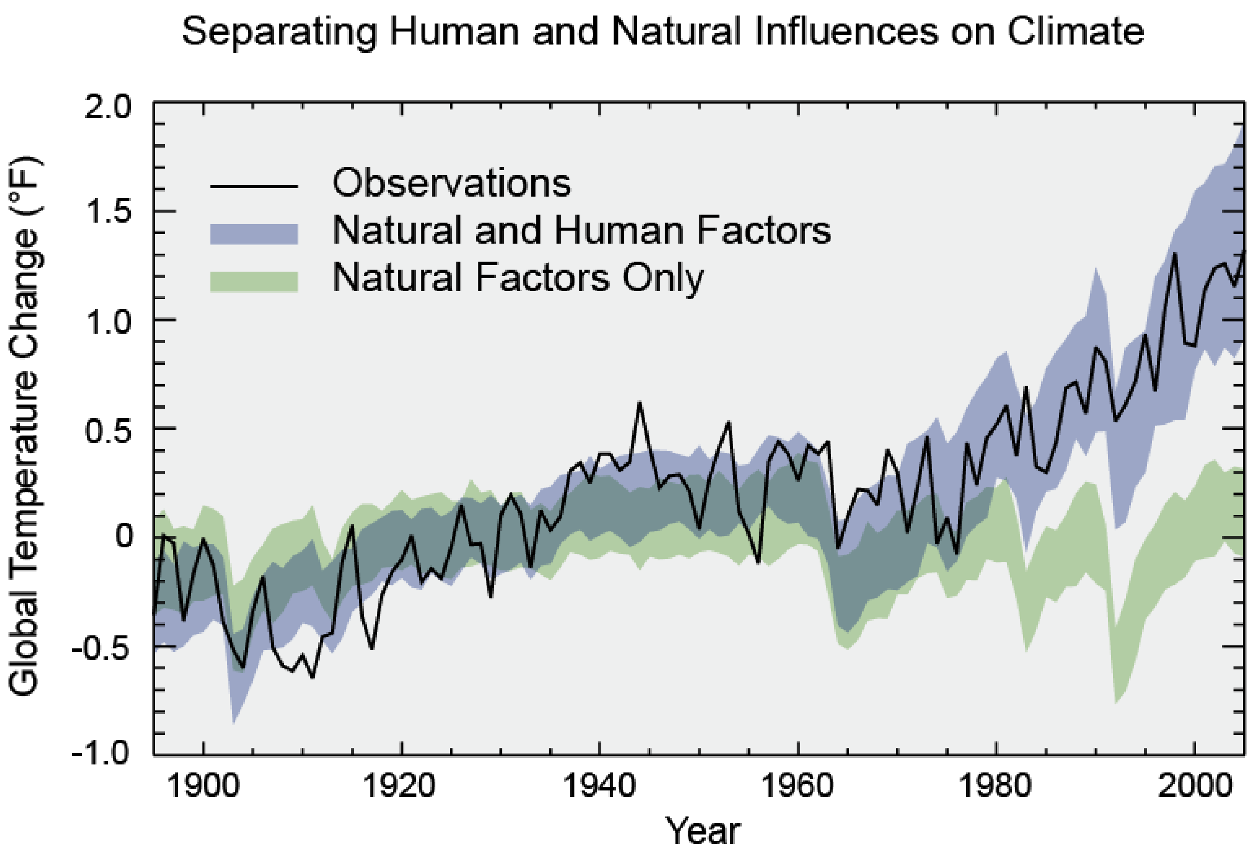

Figure 5: Results from a model experiment to compare natural warming factors with observed temperature changes since 1895. Source: Third National Climate Assessment, http://nca2014.globalchange.gov/report/our-changing-climate/observed-change#tab2-images

Climate Change Adaptation Planning

Climate change adaptation planning is the process of planning to adjust to new or changing environments in ways that take advantage of beneficial opportunities and lessen negative effects (Melillo, Richmond, and Yohe 2014).

The process of climate change adaptation planning can be similar to other resource management planning processes and generally includes the following steps:

- Identifying risks and vulnerabilities
- Assessing and selecting options
- Implementing strategies
- Monitoring and evaluating the outcomes of each strategy
- Revising strategies and the plan as a whole in response to evaluation outcomes

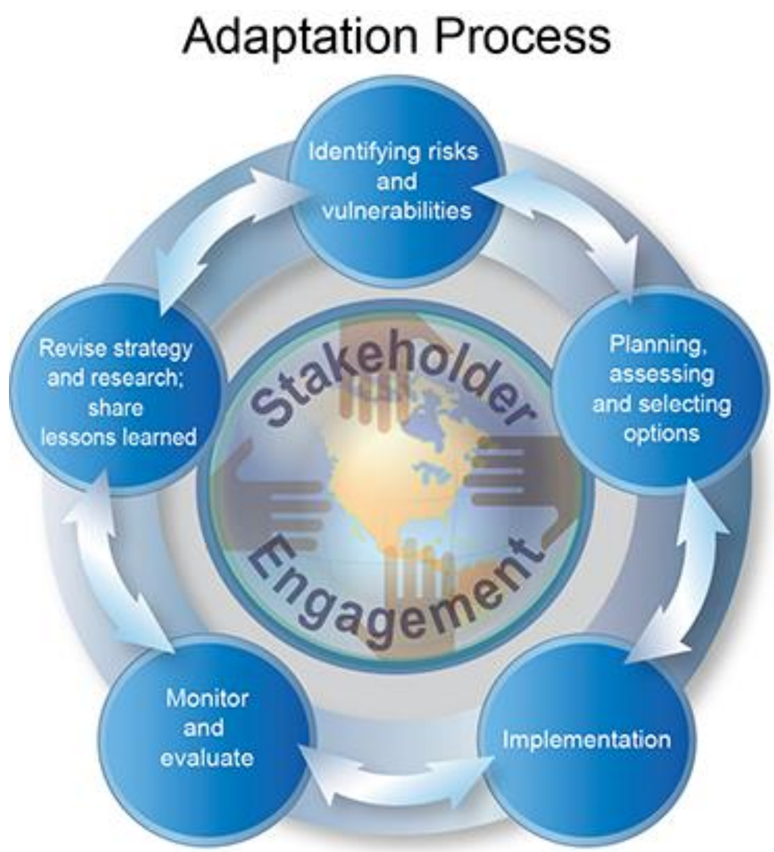

Figure 6: The Adaptation Process. Source: http://nca2014.globalchange.gov/report/response-strategies/adaptation

Key questions to ask community members, resource managers, decision makers, and elected officials when considering climate adaption are:

- What are the community's goals and objectives in the future?
- What resources or assets need to be protected from climate change impacts?
- How will the resources be protected?
- What actions are necessary to achieve the community's goals?

Adaptation strategies can range from short-term coping actions to longer-term, deeper transformations. They can meet more than just climate change goals alone and should be sensitive to the community or region; there are no one-size-fits-all answers (Moser and Eckstrom 2010).

The process of planning for climate change adaptation has already begun in many places. The federal government has required each federal agency to develop an adaptation policy (Executive Office of the President 2013). Fifteen states and 176 cities have climate change adaptation plans.

Baseline Climate Data for Coconino County

To better understand the past and current climate of Coconino County, we examined the instrumental weather and climate records from 1895 through the present. We used the PRISM (Parameter-elevation Regression on Independent Slopes Model) dataset (http://prism.oregonstate.edu/), which begins in 1895 with the first consistently recorded instrumental climate records. Climatologists refer to the period from 1895 to the present as the “instrumental record” period. PRISM uses the regional weather station observations to estimate climate variables for 2.5-mile (4-km) areas in a continuous grid across the United States (Daly et al. 2002).

The stations used in PRISM mainly come from the National Weather Service Cooperative Observer Program of the National Oceanic and Atmospheric Administration, which have the longest continuous record of weather data. However, data from other weather stations are included if they have at least 20 years of data.

PRISM accounts for variations in ***weather*** and ***climate*** due to complex terrain, rain shadows, elevation, and ***aspect***–all of which affect weather and climate across Coconino County.

Temperature in Historical Perspective

Between 1895 and 2017, the annual average temperature across Coconino County was 52.3° F. However, year-to-year the averages have ranged from below 49.9° F in 1912 to 55.4° F in 2017. Although year-to-year changes in temperature are natural and expected in this region, we see a fairly consistent increasing trend in annual temperatures since the mid-1980s. In Figure 7, the straight horizontal line represents the long-term average, orange bars represent years with above-average temperatures, and blue bars represent years with below-average temperatures. **Almost every year since 1985 has seen average annual temperatures above the long-term average**.

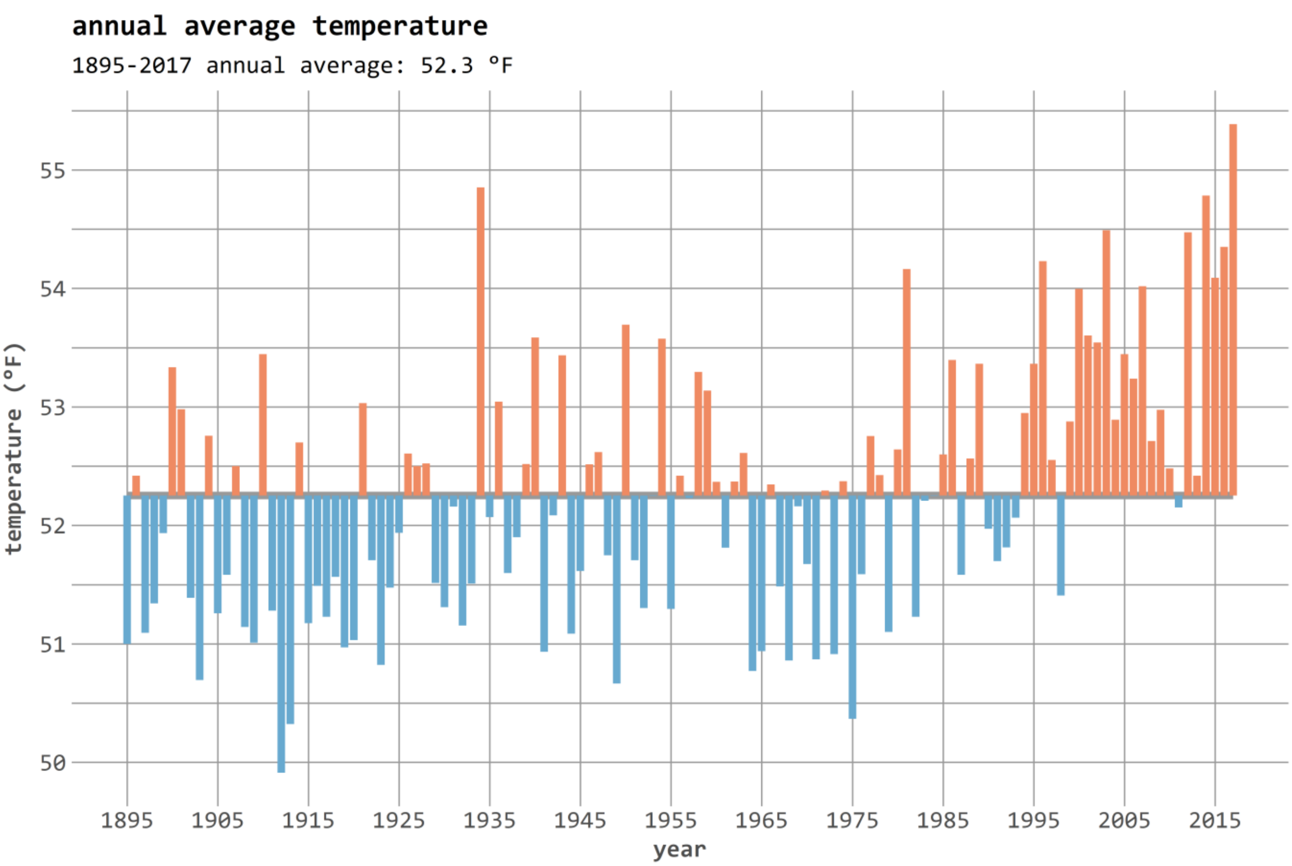

Figure 7: Average annual temperatures for Coconino County from 1895–2017.

Disaggregating temperatures as average daily maximum, average daily minimum, as well as overall average allows us to identify patterns in the ways in which warming is impacting a region. *Maximum* annual average temperature tells us the average of all the warmest (typically afternoon) daily temperature readings in an area. *Minimum* annual average temperature tells us the average of the lowest temperature readings, which typically occur in the early morning. Overall average is the average of both maximum and minimum temperatures for an area over a given time.

In Figure 8, we see that *minimum* annual average temperatures (shown in yellow) for Coconino County have been rising faster than *maximums* (shown in red). This pattern indicates that **the warming trend is mostly being driven by rising low temperatures**, such as days not being as cold and fewer cold days each year (see Temperature Extremes section below).

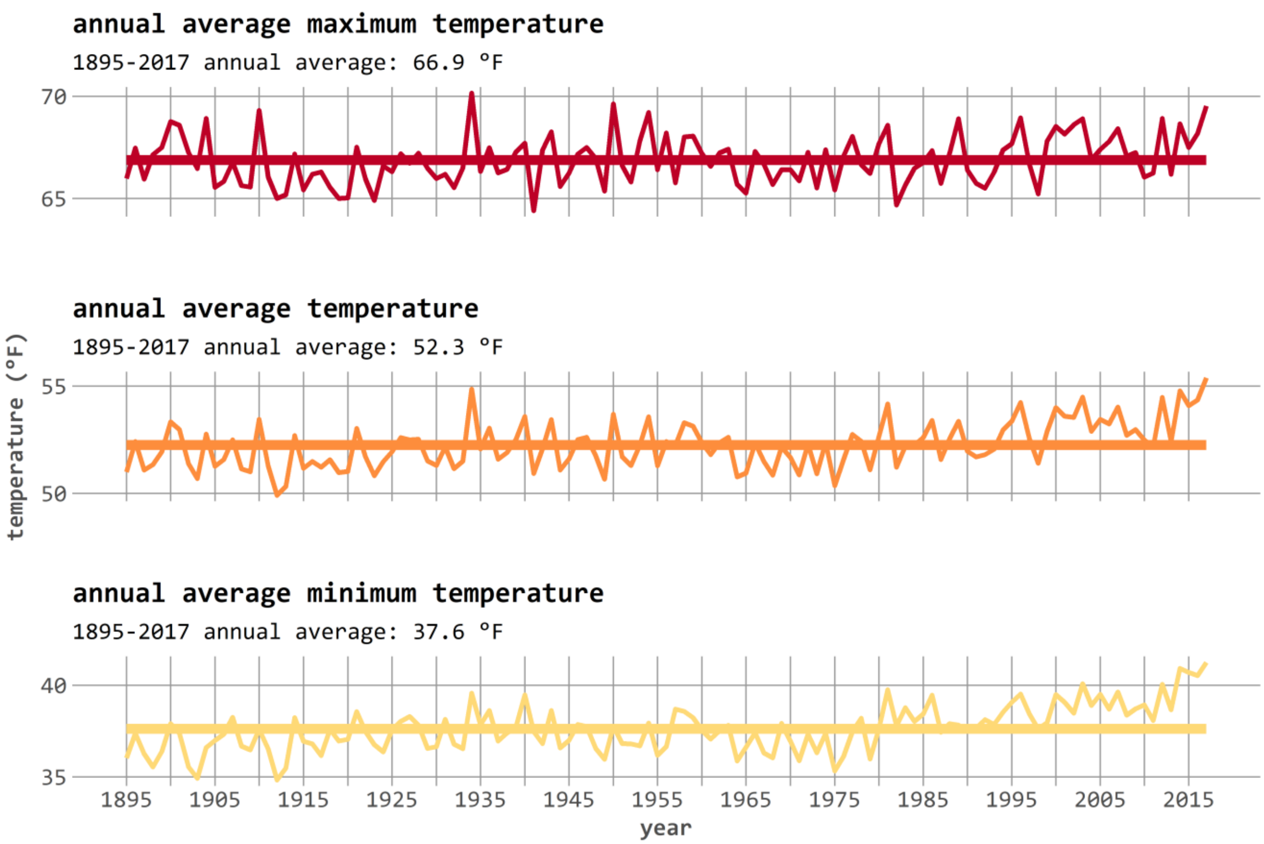

Figure 8: Annual average maximum (red), minimum (yellow), and overall average (orange) temperatures for Coconino County from 1895–2017.

Precipitation in Historical Perspective

As is normal in the southwestern United States, precipitation across Coconino County is highly variable and has ranged from over 22.6 inches in 1905 to below 6.9 inches in 1956. The average precipitation across Coconino County between 1895 and 2017 was 13.7 inches per year (Figure 9). In Figure 9, green bars represent years with above-average precipitation and brown bars represent years with below-average precipitation.

Coconino County has experienced two periods of generally above-average precipitation (***pluvials***), which are noted with light green shading. The most distinct pluvials occurred from 1905 through the mid-1920s, and again in the late 1970s through the mid-1990s. Multi-year drought periods (multiple years with below-average precipitation), noted with light brown shading, occurred in the late 1800s to early 1900s, 1950s, and early 2000s.

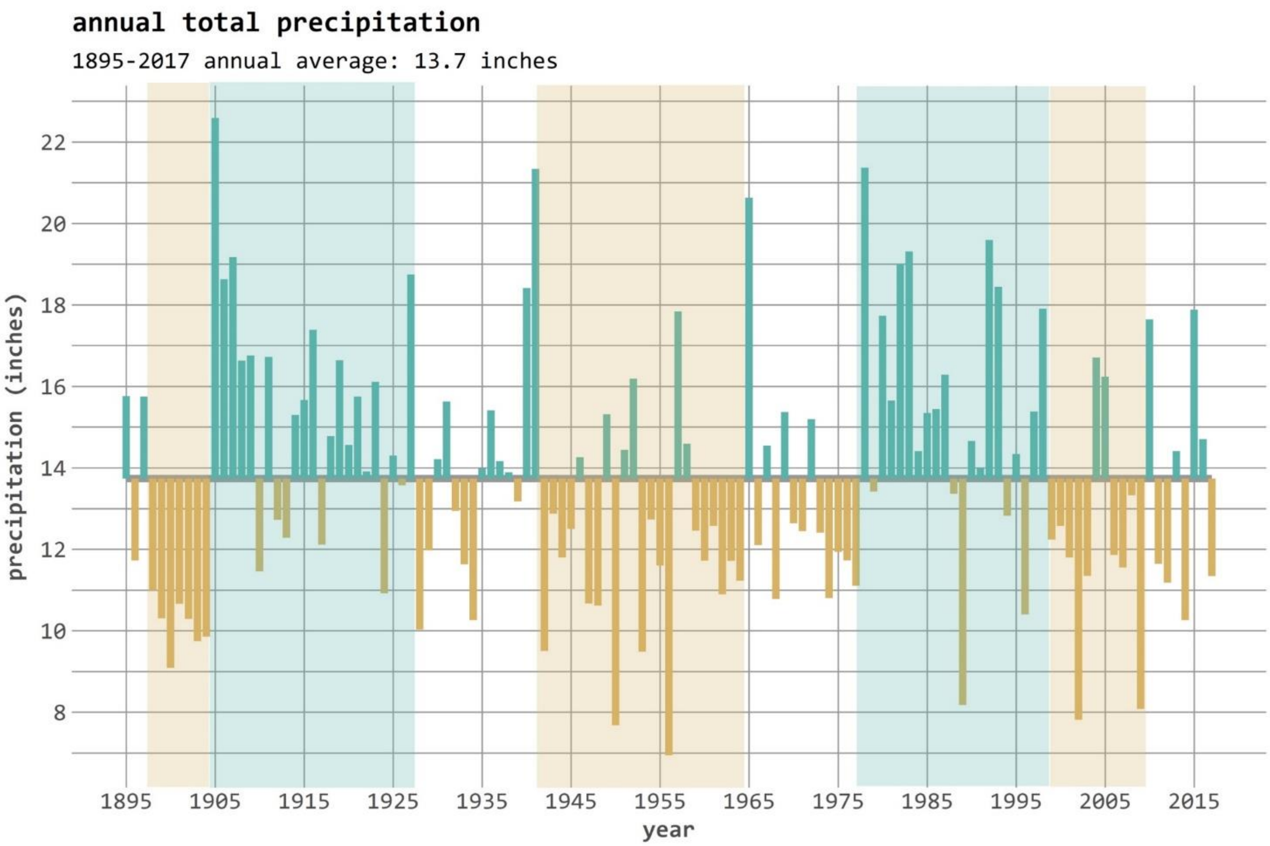

Figure 9: Average annual precipitation for Coconino County 1895 – 2017.

Temperature Extremes

Temperature extremes data can be calculated using a single weather station in a relevant location. Using data from the weather station at Flagstaff Pulliam Airport, we can track daily extreme temperatures back to 1950. Prior to 1950, data collection at the airport was inconsistent and, therefore, the data are not reliable enough to use in a time-series analysis such as the ones presented below.[3]

Since 1950, the average highest daily maximum temperature (the average of the hottest temperature for each year recorded at the airport) was 91.2° F; the highest recorded daily maximum in that time period is 97° F in 1973 (Figure 10).

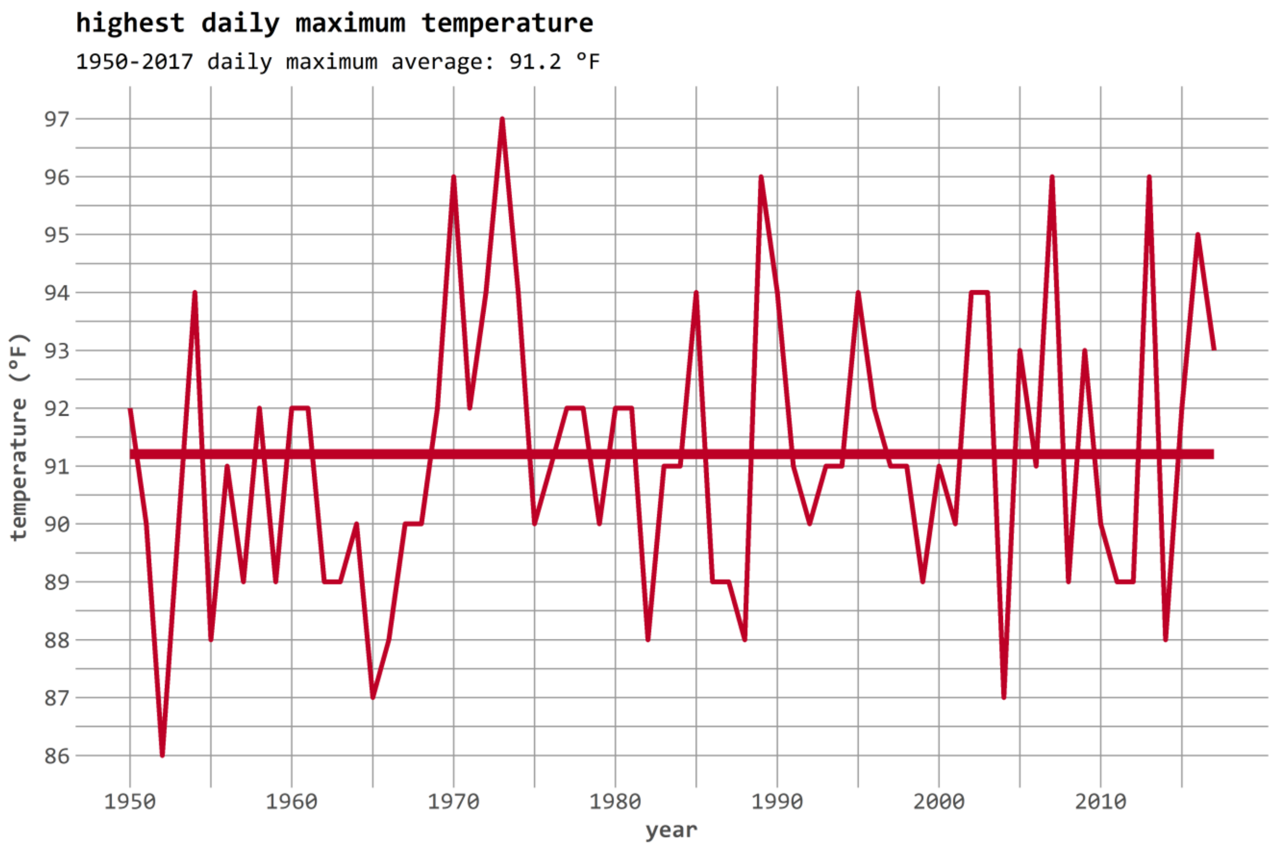

Figure 10: Maximum daily temperatures recorded at the Flagstaff Pulliam Airport for each year from 1950–2017.

[3] The data from the airport weather station are available from the NOAA National Centers for Environmental Information (NCEI) Daily Observational Data Map (https://gis.ncdc.noaa.gov/maps/ncei/cdo/daily).

We also looked at how many days per year exceeded a comfortable heat threshold of 90° F for Flagstaff residents (Figure 11). While there are a number of definitions of human comfort or heatwave thresholds, here we chose to rely on a threshold suggested by Flagstaff residents: 90° F. Since 1950, Flagstaff has experienced an average of two days per year in which the daily maximum temperature has risen above 90° F. In some years, which are blank in the figure, temperatures never reached the 90° F threshold. In 1974 and 1990 temperatures exceeded the 90° F threshold 12 and 11 times, respectively. In 2017, Flagstaff experienced seven days above the 90° F threshold.

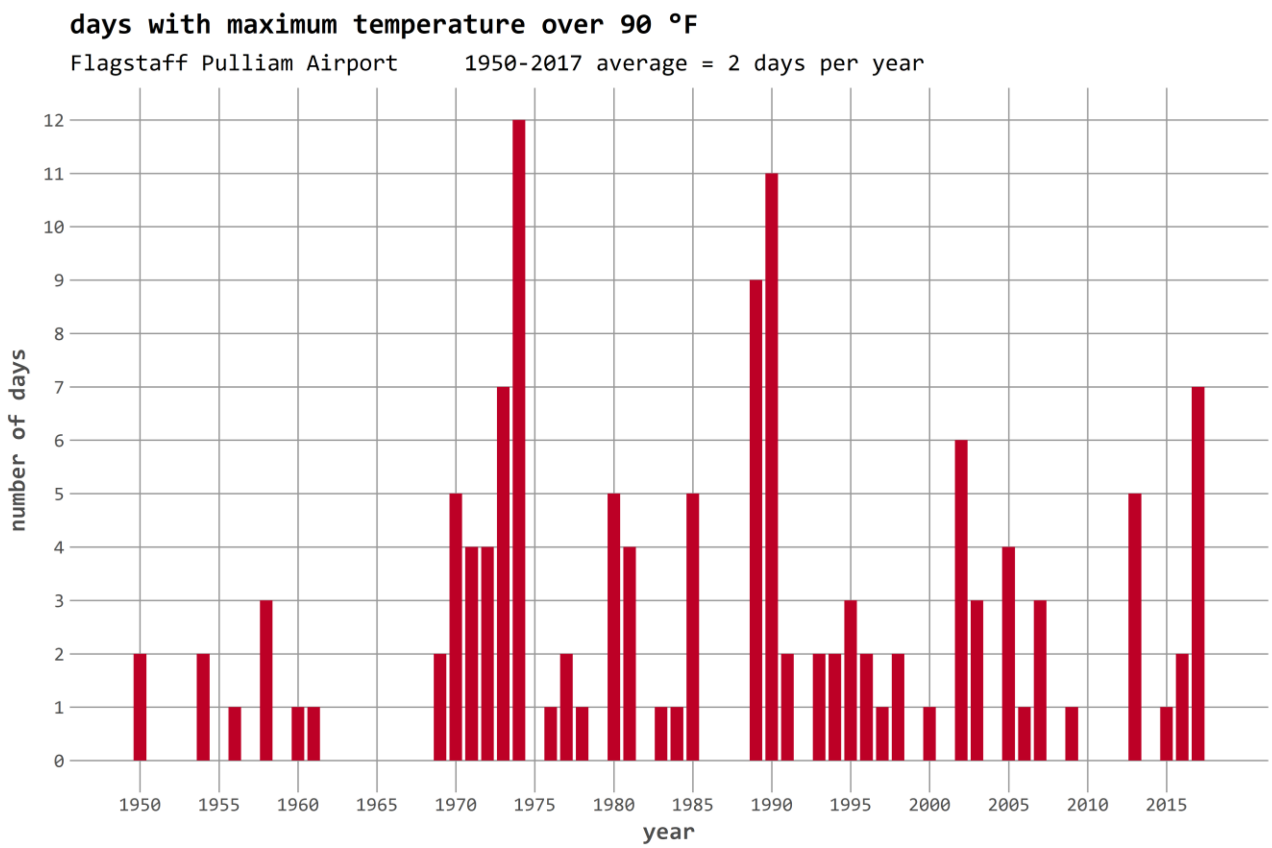

Figure 11: Number of days in which the maximum temperature exceeded 90°F at the Flagstaff airport from 1950–2017.

The average lowest daily minimum temperature from 1950–2017 (average of the lowest temperature for each year recorded at the airport) is -9.3° F. The low daily minimum temperatures have ranged from -23°F in 1978, 1985, and 1990 to as high as 7°F in 1981 (Figure 12). Since 1991, the **lowest daily minimum temperature has tended to be above the long-term average**.

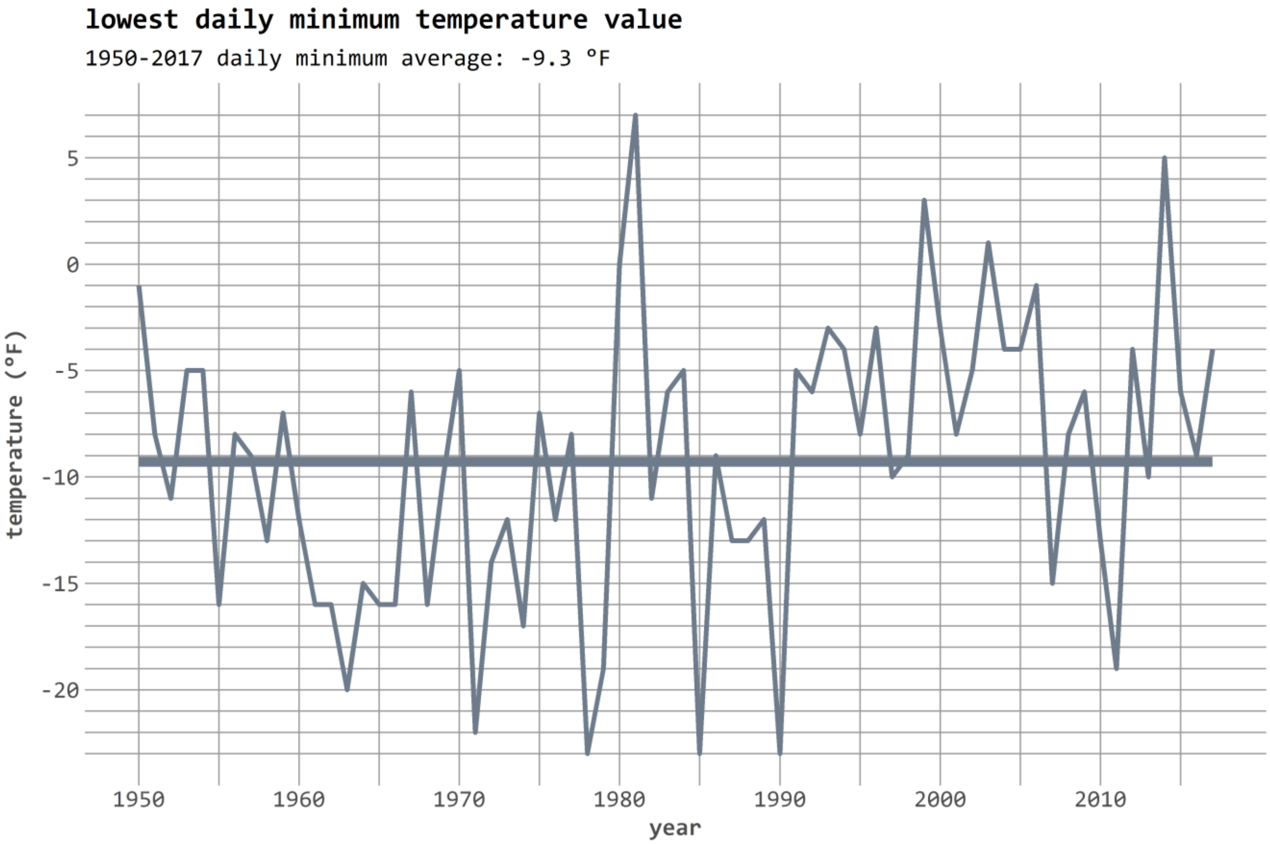

Figure 12: Lowest daily minimum temperatures recorded at the Flagstaff Airport from 1950-2017.

Given the importance of Flagstaff's winter tourism, we also examined the minimum temperature threshold of 32° F (temperature at which snow melts). Since 1950, Flagstaff has averaged 197 days per year with minimum temperatures below 32° F (Figure 13). In Figure 13 the straight horizontal line represents the average number of days with temperatures below 32° F, blue bars represent years in which days below 32° F have been higher than the long-term average, and orange bars represent years in which those days have been below the long-term average.

The number of days has ranged from a maximum of 230 in 1971 to a minimum of 170 days in 1992. Consistent with the data showing that temperature trends are being driven by increasing low temperatures (Figure 8), we note that **in the 31 years since 1985, Flagstaff has experienced fewer cold days (below 32° F) than in the time period from 1950–1985**. As is expected with natural temperature ***variability***, there have still been some years above the long-term average during this more recent period.

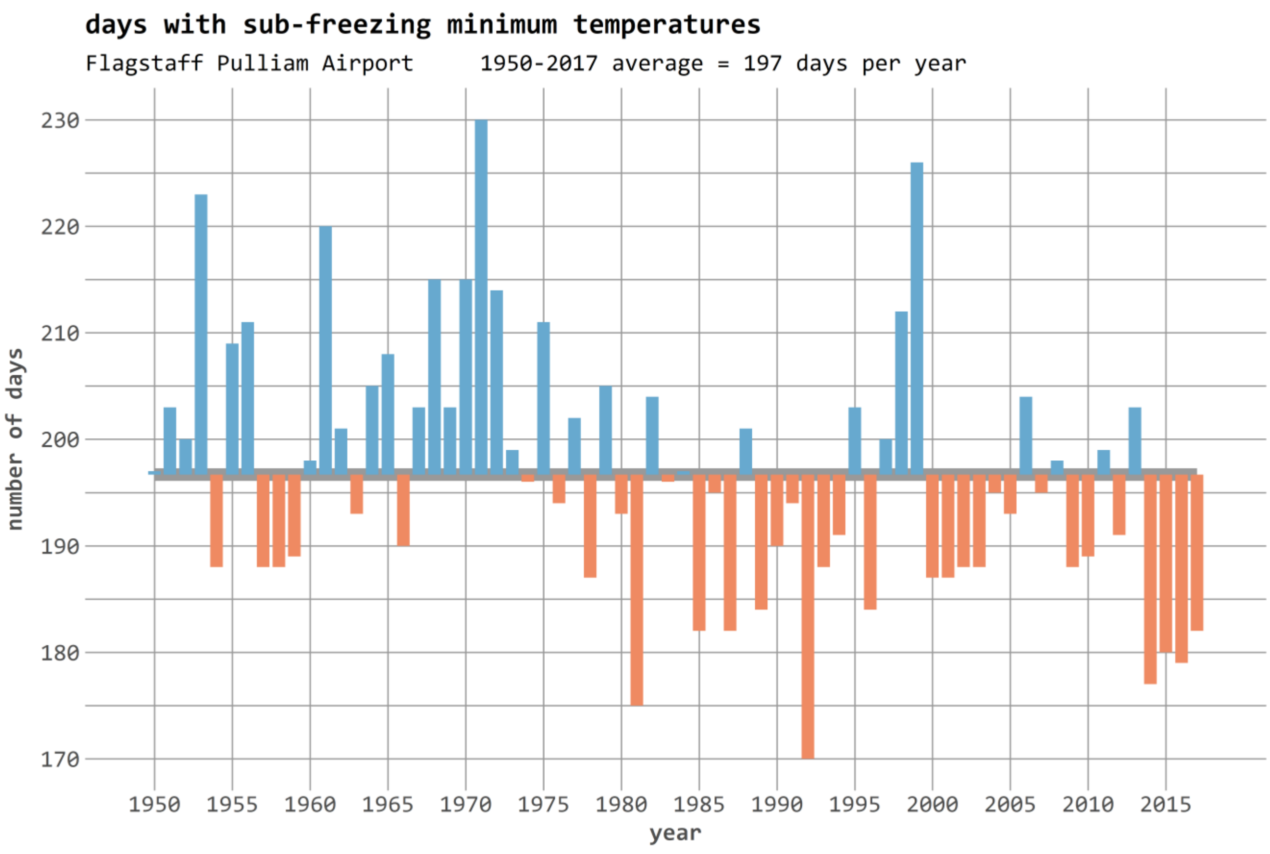

Figure 13: Number of days in which the minimum temperature fell below 32° F at the Flagstaff airport from 1950–2017.

The growing season is generally considered the time between the last freeze (<32° F) in the spring and the first freeze (<32° F) in the fall. In Coconino County, the average growing season since 1950 has been 114 days per year (Figure 14). The shortest season was in 1968, with only 74 days. The longest season was 164 days in 1992. **Eight of the last 10 years have seen above average growing seasons in Flagstaff.**

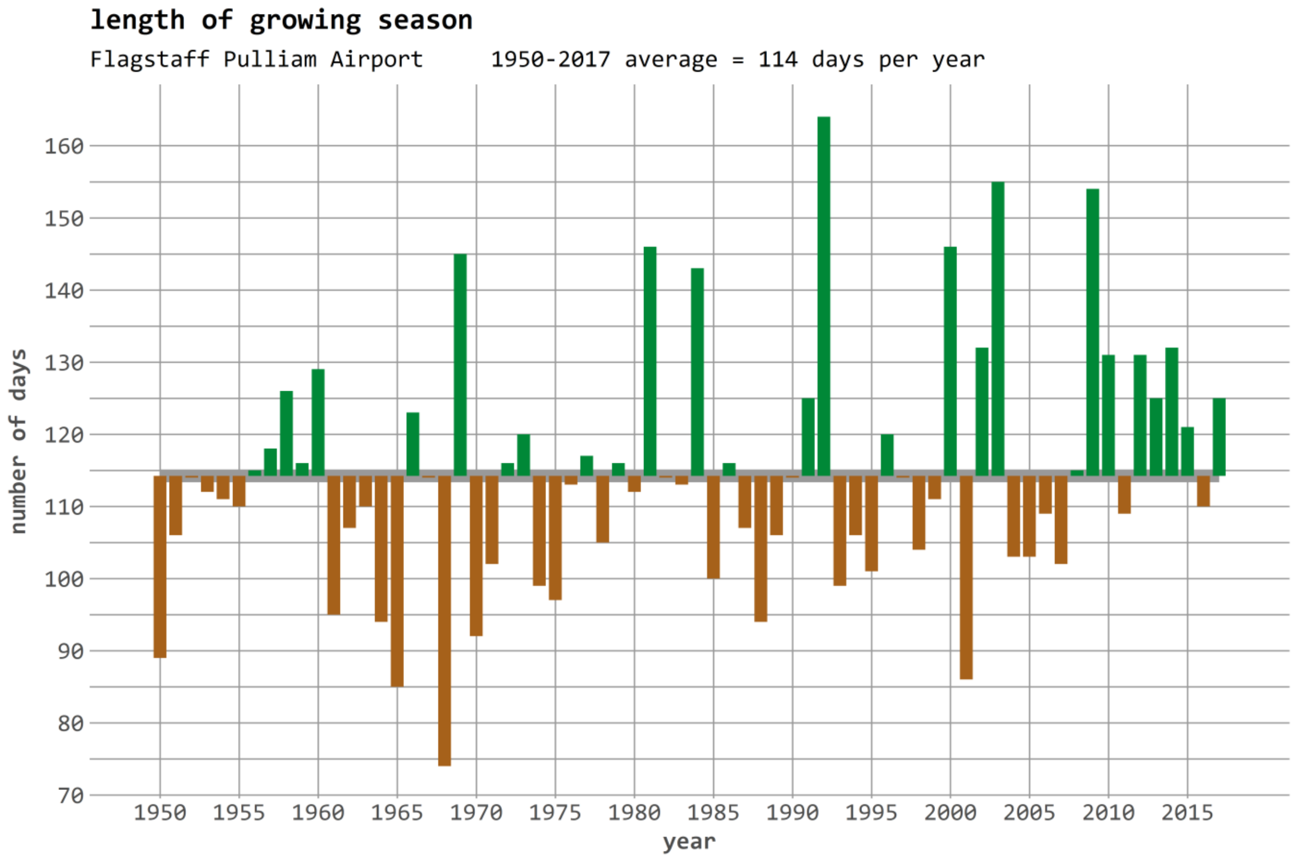

Figure 14: Length of growing season based on temperatures at Flagstaff Airport 1950–2017.

Future Temperature and Precipitation Projections for Coconino County

The Intergovernmental Panel on Climate Change (IPCC), which is the international body convened to assess climate changes and impacts across the globe, has developed a set of four ***scenarios*** to project possible future climates for the world as a whole. Different levels of GHGs released into the atmosphere will have different impacts on warming temperatures. In order to show this range of possible outcomes, climate scientists use ***Representative Concentration Pathways*** (RCPs), which are based on the current rates of GHG emissions and estimated emissions up to 2100, based on assumptions about global levels of economic activity, energy sources, population growth and other socio-economic factors. These scenarios are then used in Global Climate Models (GCMs) to estimate future global average temperatures.

GCMs cannot firmly predict future climate patterns, but they are useful tools that point us toward likely futures, based on the best currently available science. There are two main sources of uncertainty regarding ***climate projections*** that should be kept in mind when considering future climate scenarios. First, there is a range of possible ways humans will choose to manage our emissions of GHGs in the future. The four different RCPs are one way to explore these different possible emissions scenarios and generate climate projections for each one. A second source of uncertainty is the ability of the GCMs to capture the complex global climate system. No single climate model can perfectly imitate such a complex system. For example, climate scientists tend to trust models to project the *direction* of change (such as temperatures rising), but they have less confidence in the ability of models to project the ***magnitude of change*** (exactly how much temperatures will rise). The approach to reducing this source of uncertainty is to use the average projections from many different models rather than rely on any single model.

The following summaries of projections–both for the globe and for Coconino County–use both RCPs and an average of multiple climate models to reduce uncertainty and provide reasonable estimates of possible future climates for both scales of analysis. Table 1 summarizes the assumptions and projections for all four RCPs.

Table 1: Assumptions and Projections for each Representative Concentration Pathway.

Scenario	Assumptions	Projected Temperature Increase
RCP 2.6 *blue line and shading*	"Best Case Scenario" - assumes that through policy intervention, GHG emissions are reduced by 2020 and decline to around zero by 2080, leading to a slight reduction in today's GHG levels by 2100.	Global average temperature increase of 2.5° F (1° C) by the year 2100.
RCP 4.5 *aqua bar shown only to the right of the chart*	Assumes that GHG emissions will peak at around 50% higher than year 2000 levels in about 2040 and then fall.	Global average temperature increase of 4° F (1.8° C) by 2100.
RCP 6.0 *yellow bar shown only to the right of the chart*	Assumes that emissions will double by 2060, then fall but still remain above current levels through 2100.	Global average temperature increase of 5° F (2.2° C) by 2100.
RCP 8.5 *red line and shading*	"Worst Case Scenario" - Assumes GHG emissions continue to grow at current rate through 2100.	Global average temperature increase of more than 8° F (3.7° C) by 2100.

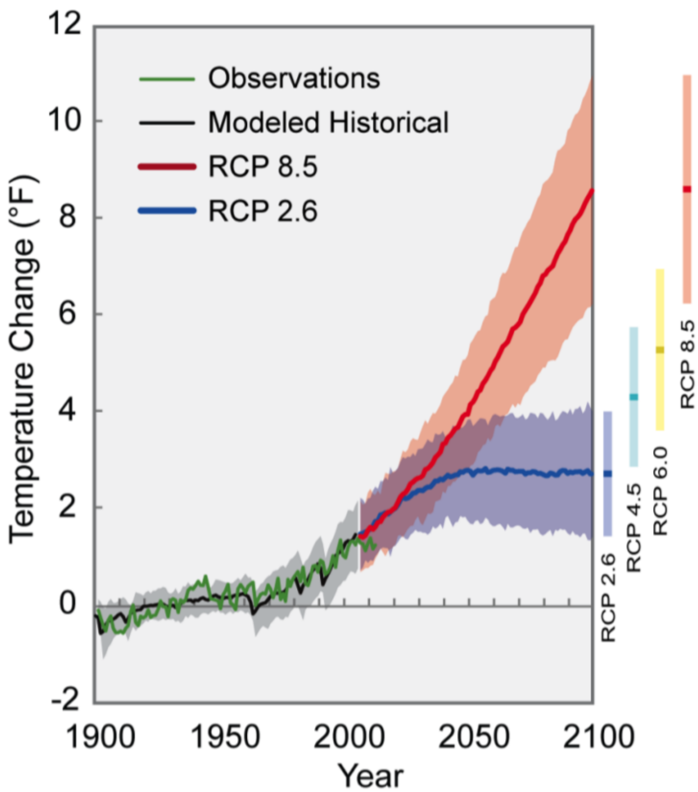

Figure 15: Projected global temperature increases using the four Representative Concentration Pathways (RCP) scenarios. Source: https://nca2014.globalchange.gov/report/our-changing-climate/future-climate-change

GCMs that were built to cover the whole globe can be focused on smaller regions through a process of ***downscaling***. We used ***statistically downscaled*** climate models to compile climate projection data for Coconino County, which is a small enough area to capture the trends expected to affect the county, but big enough that we have confidence in the accuracy of the projections. In this study, we analyzed downscaled climate projection data from one model run of 30 different global climate models using two of the scenarios described in Figure 14–RCP 4.5 and RCP 8.5. At present, RCP 4.5 represents an optimistic, lower-emissions scenario, while RCP 8.5 is closer to our current, higher emissions trajectory.

Downscaled model projections for Coconino County (Figure 16) show a range of possible future temperature increases, from almost 6° F higher than the 1986–2005 average for RCP 4.5 (orange line and shading) to over 10° F higher for RCP 8.5 (red line and shading).[4] If GHG emissions continue at their current rate, the county could be significantly warmer, as indicated by the higher (RCP 8.5) scenario. **The projections of Coconino**

[4] Annual values of differences in average temperature relative to the period 1986-2005 and based on daily 1/16-degree Localized Constructed Analogs statistical downscaling of CMIP5 global climate model projections (loca.ucsd.edu) using RCPs 4.5 and 8.5. Averages are computed from data overlying Coconino County.

County's average temperature are even higher than projections for the global average temperature.

Coconino County's current annual average temperature is 52.3° F; by the end of the century it could be between 58° F (lower scenario) and 63° F. For comparison, Sierra Vista, AZ's annual average temperature now is approximately 63° F. Projections for the year 2050 range from 4 -5° F higher than the current average, which is similar to the current average temperature of Albuquerque, NM.

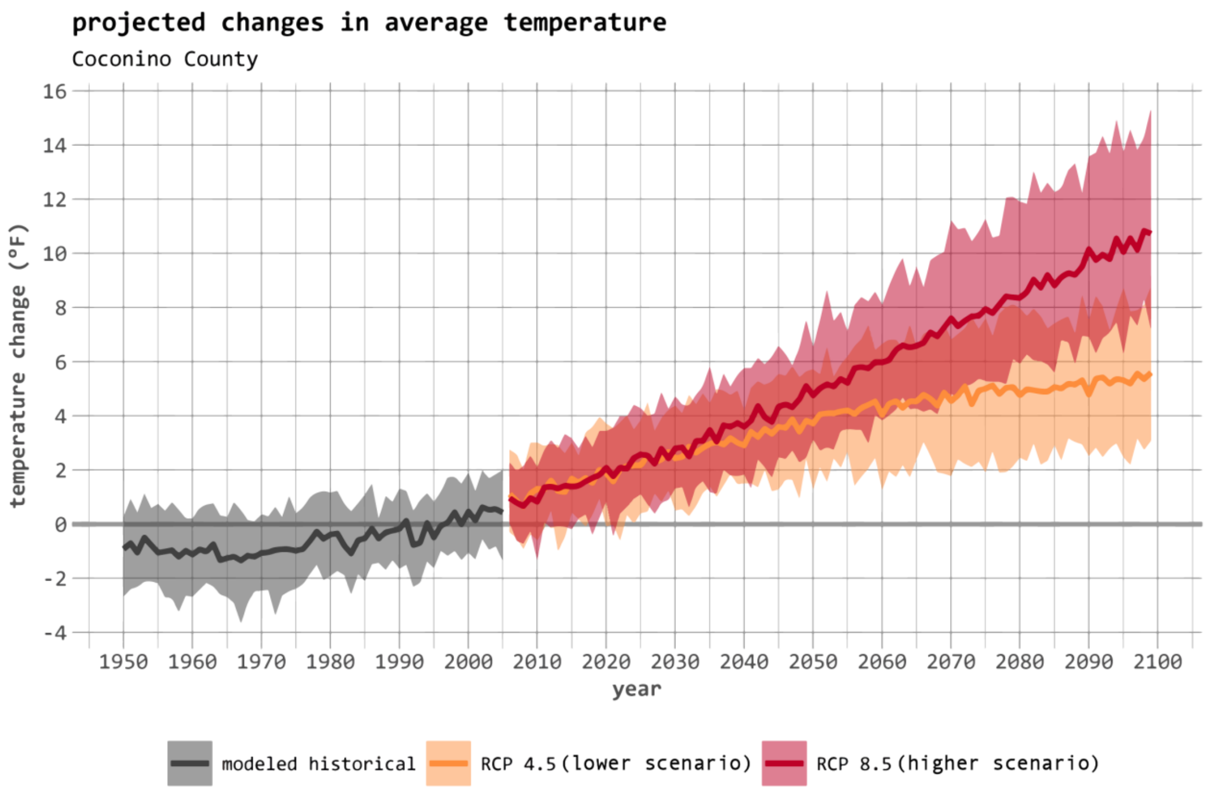

Figure 16: Downscaled model projections for Coconino County show a range of possible future temperature increases, from 3° F higher than the 1986–2005 average for RCP 4.5 (orange line), to 10° F higher for RCP 8.5 (red line).

While the projections for *temperature* show possible increases in both scenarios, **the projections show little-to-no change in annual average *precipitation* for Coconino County, even under the higher RCP 8.5 scenario** (**Error! Reference source not found.**, dark blue line). Figure 17 shows the projected percent change in total precipitation for Coconino County from the 1986–2005 average. None of the models show more than a few percentage points of change in either direction (more or less rain). The current average precipitation in the county is about 13.7 inches per year. The model projections show a possible change of about 5% in either direction (higher or lower), which translates to about half an inch more or less each year.

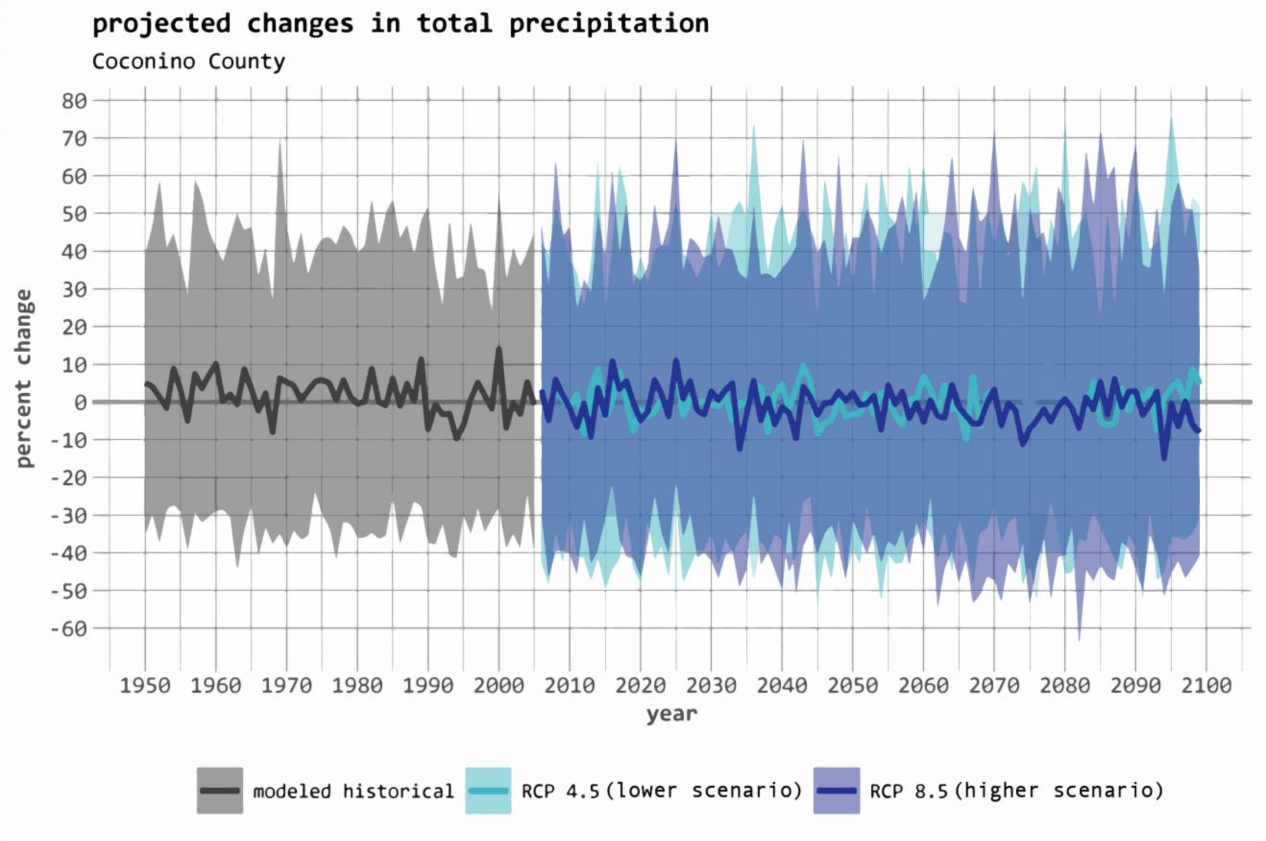

Figure 17: Downscaled projections of annual average precipitation for Coconino County, using RCP 4.5 and 8.5. No trend in future precipitation is clear from the analysis.

It is important to note that modeling precipitation for this region has proven very difficult, due to the multiple phenomenon that influence this region, including the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation PDO), and the North American Monsoon. Future projections about annual average precipitation in the Southwest region are much less certain than projections of future precipitation in other parts of the country (Gershunov et al. 2013)[5]. However, **even if there is no change in total precipitation, Coconino County could become much drier as projected warmer temperatures will mean more evaporation of surface water and more transpiration (use of water by plants), which will further dry the soil, with the potential changes in soil moisture particularly large in the winter and spring** (Figure 18)**.** Changes related to storm intensity and patterns are discussed below.

[5] The authors of the 2013 Assessment of Climate Change in the Southwest United States expressed only medium-low confidence in projections related to precipitation changes in the region (Overpeck et al. 2013).

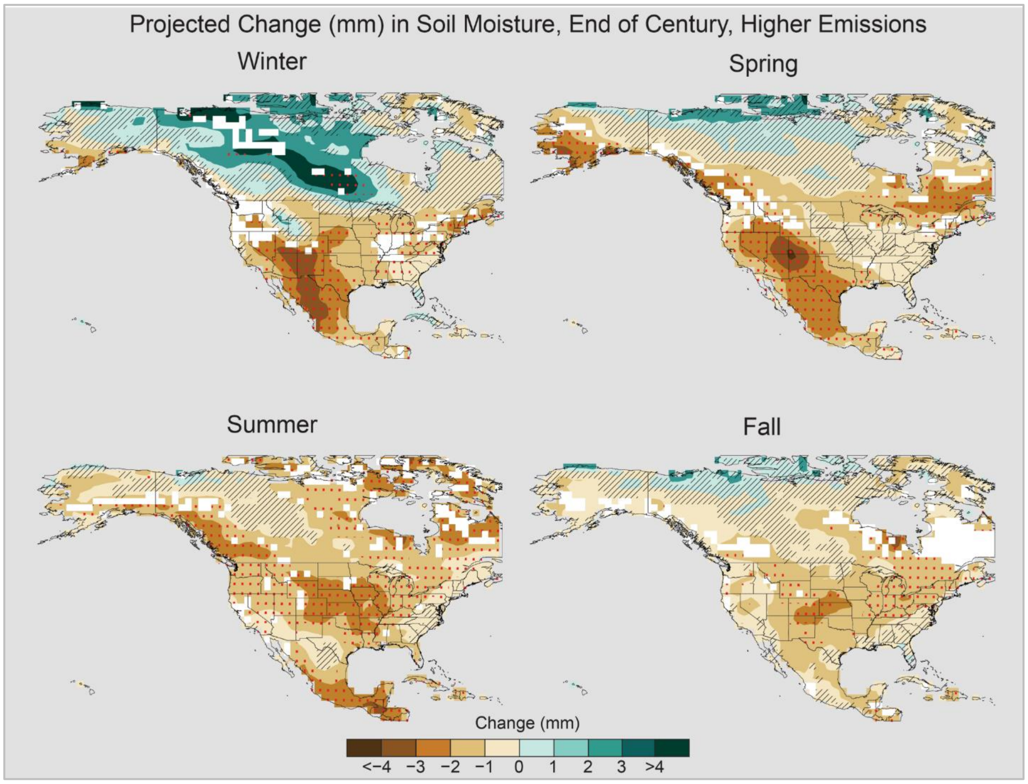

Figure 18: Projected changes in soil moisture by 2100 using the high emissions scenario. Source: https://science2017.globalchange.gov/chapter/8/

Recent research on the North American Monsoon points to changes that may affect Coconino County and Flagstaff. Warmer temperatures have expanded and intensified the North American monsoon ridge, resulting in fewer storms across Arizona during the peak of the monsoon season (late-July to mid-August) (Lahmers et al. 2016). This generally has led to a decline in seasonal precipitation totals during the last 30 years (1980–2010) as compared to the period from 1948–1979, particularly in low-elevation desert areas (Luong et al. 2017). Even though there have been fewer storms, the most extreme storms have become more intense (as measured by amount of precipitation and wind gusts). This is because a warmer atmosphere can hold more moisture, which in turn can contribute to more extreme precipitation events. Between 1980 and 2010, during the latter part of the monsoon (mid-August to September), some higher elevation areas have experienced increases in total precipitation amounts as thunderstorms that develop over this terrain (such as parts of northern Arizona) have moved less frequently into the lower deserts. These storms have stayed in more mountainous areas, which also increases the flood potential in those areas (Lahmers et al. 2016). These patterns are projected to continue into the future--**while the overall average amount of precipitation may not change (or**

may decrease), we may receive that precipitation in fewer, but more intense storms (Castro 2017).

Projected Temperature Extremes

The average number of days above 90° F in Flagstaff (see Figure 11) is 2 days per year (between 1950 and 2017). **The projected change in the number of days above 90° F** (Figure 19) **range from just under 30 days per year (lower scenario) to as many as 80 days per year (higher scenario) by the end of this century.**

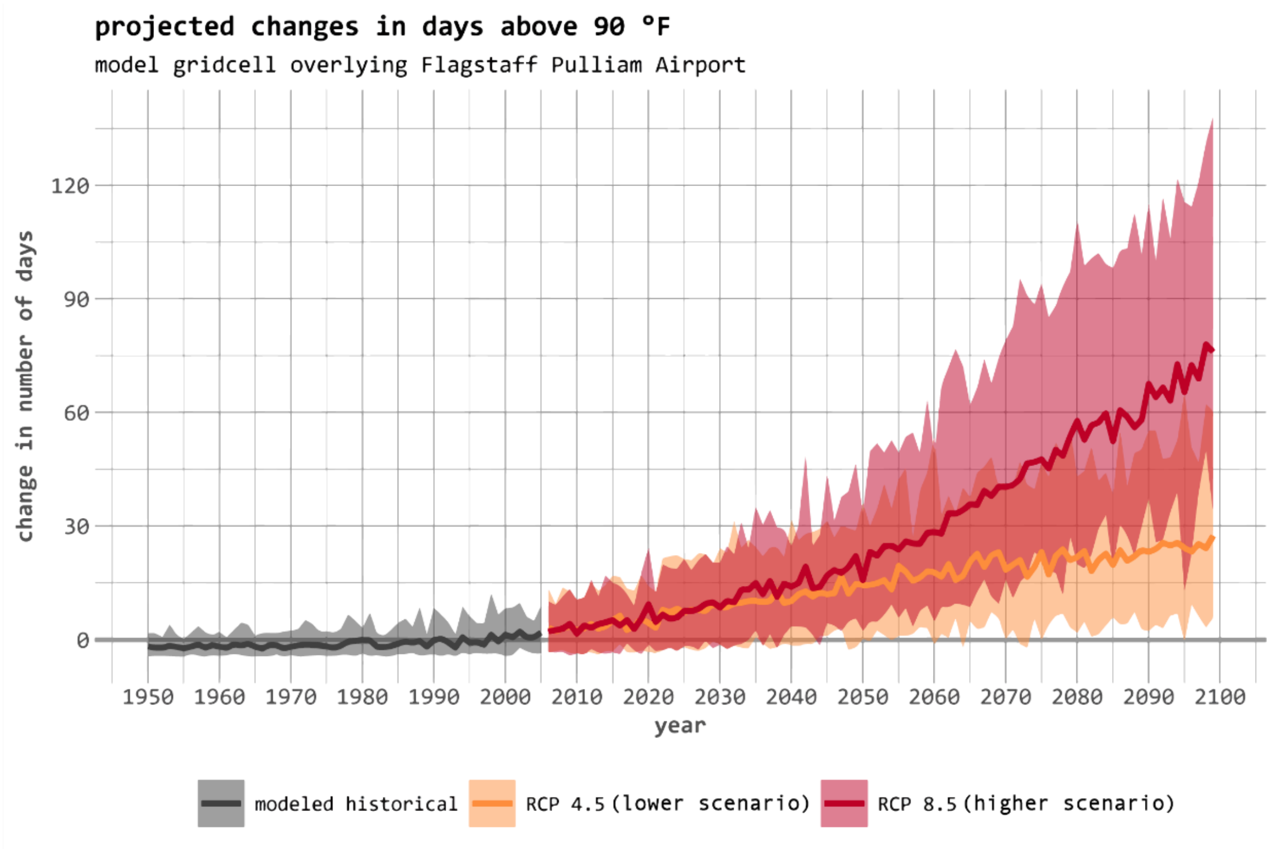

Figure 19: Projected changes in number of days in which maximum temperatures reach 90° F in Flagstaff.

The historical record indicates that Flagstaff has experienced an average of 197 days per year in which the minimum temperature reaches 32° F (see Figure 13). Projections for Flagstaff indicate that the number of days that fall below the freezing point could decrease by 45 to 90 days, for RCP 4.5 and 8.5 respectively (Figure 20). **By the year 2100, Flagstaff could experience as few as 100 days that reach freezing temperatures**.

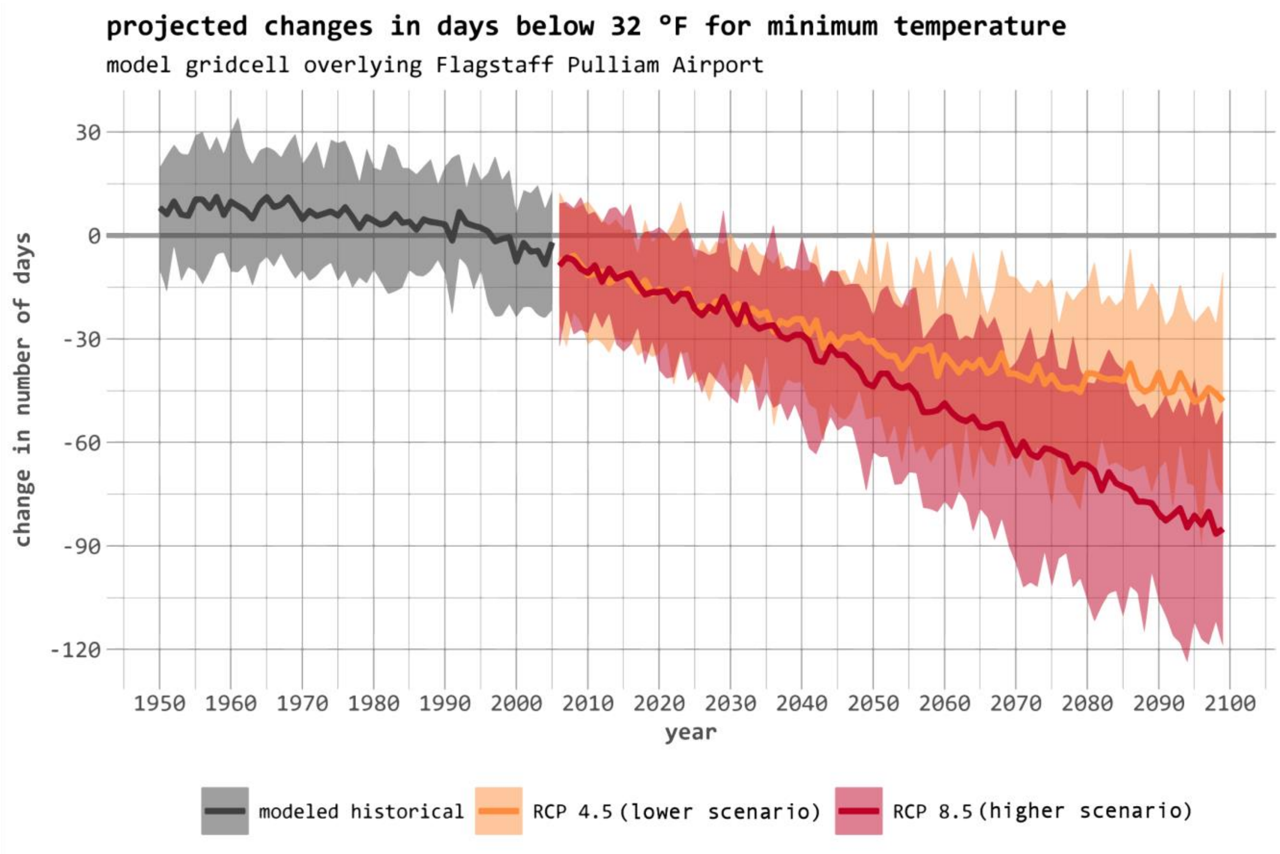

Figure 20: Projected changes in number of days in which minimum temperatures fall below 32° F.

Based on the projected temperature changes for Flagstaff, the growing season is likely to change as well (Figure 21). The season is likely to increase by between 40 days (RCP 4.5) and 70 days (RCP 8.5) by the end of the century.

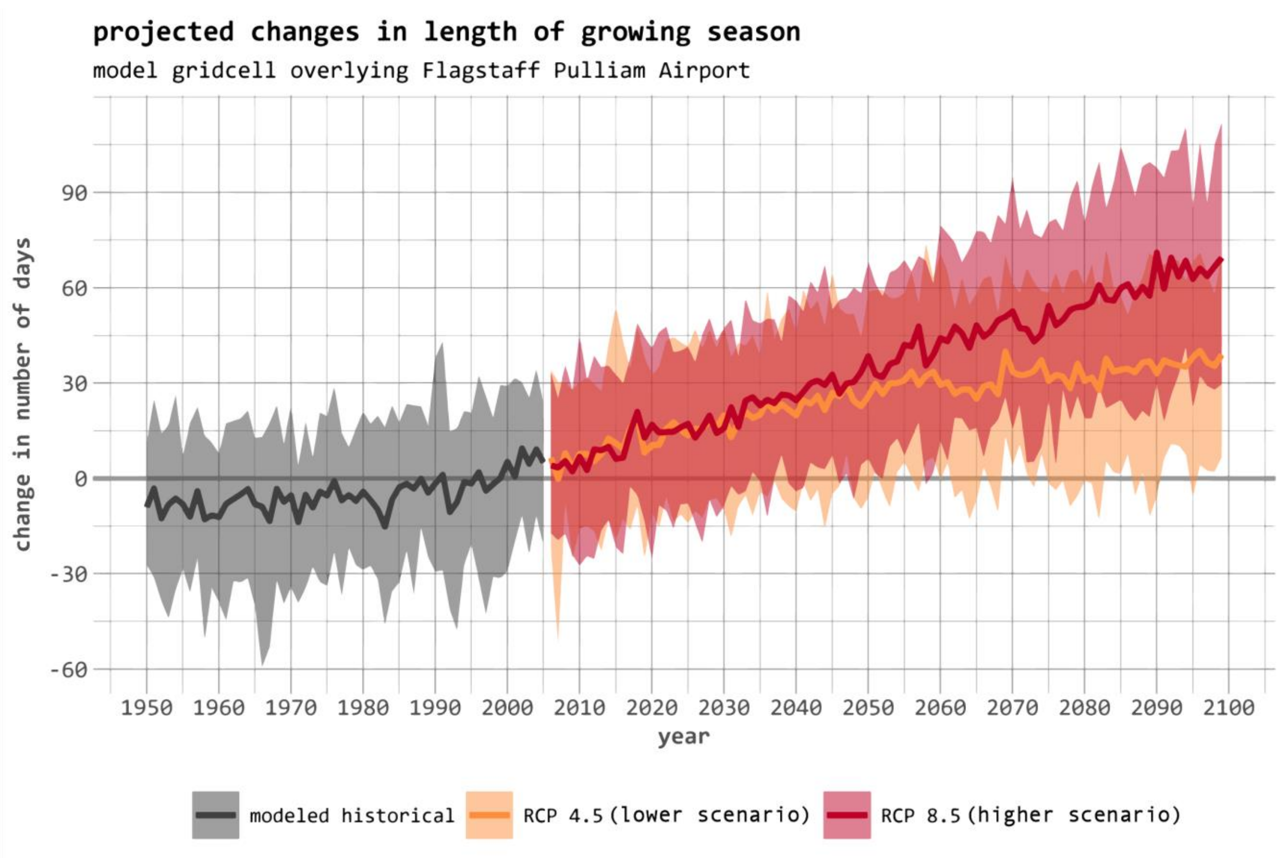

Figure 21: Projected changes in length of growing season for Flagstaff.

Climate Summary

Based on an examination of Flagstaff and Coconino County's historic and projected climate, we see a clear warming trend. Although natural variability will always exist, meaning some years will be warmer and some colder, the overall trend is toward warmer temperatures; in particular, low temperatures are not, and will not be, as low as in the past. Although there are no clear trends in precipitation, the warmer temperatures will contribute to an overall drying trend. Some key changes that are likely to affect Flagstaff and Coconino County include:

<u>Changes in Temperature</u>

- Average temperatures in Coconino County have been rising since about the mid-1980s. Almost all years since 1985 have had average annual temperatures above the long-term average.
- Minimum temperatures, which manifest as days not being as cold and as fewer cold days per year, are largely driving the upward trend in temperatures.
- These trends are projected to continue into the future. Scenarios for Coconino County indicate that average temperatures could be 5° F above the current average (52.3° F) by 2050 and more than 10° F above the current average by the year 2100.

<u>Changes in Precipitation</u>

- Precipitation has historically been variable, as is normal for this region. There is no clear trend toward changes in average precipitation amounts in Coconino County.
- The same variability is present in future projections of precipitation with no clear indication about changes in overall average amounts.
- Rising temperatures will, however, increase evaporation and transpiration rates, which will lead to drier soils and contribute to more frequent and severe drought.
- Rising low temperatures also indicate a likely change from precipitation falling as snow to more of the precipitation falling as rain during colder months of the year.

<u>Changes in Extreme Temperatures</u>

- From 1950–2017, the average number of days above 90° F in Flagstaff was 2 days per year. The projected change in the number of days above 90° F is as high as 80 days per year by the end of this century.
- On average, Flagstaff has experienced 197 days per year in which minimum temperatures drop below freezing (32° F). By the year 2100, Flagstaff could experience as few as 100 days that reach freezing temperatures.

The implications of these changes for Flagstaff will be discussed in climate vulnerability assessment process, which will be completed in the spring of 2018.

Additional Resources to Support Climate Change Adaptation Planning

The National Climate Assessment; Adaptation Chapter
http://nca2014.globalchange.gov/report/response-strategies/adaptation

Climate Adaptation: The State of Practice in U.S. Communities
http://kresge.org/climate-adaptation

Climate Adaptation Knowledge Exchange
http://www.cakex.org/

Glossary

Aspect: A surface feature of land: the direction a slope faces. A slope's aspect determines the amount of sun exposure it receives, so aspect affects temperature, humidity, and the type and amount of vegetation in a particular place.

Climate: The averages and patterns of weather over time for a particular area, such as temperature, precipitation, humidity, and wind.

Climate projections: Estimates of future climatic conditions, usually made with mathematical models using different rates of greenhouse gas emissions to create different possible future scenarios.

Climate trends: Changes in climate in a particular area that have been observed over time, such as increases or decreases in average temperatures or the amount of annual precipitation.

Downscaling: Various methods that use data from global climate models to derive climate information for smaller areas of the world, such as specific regions (U.S. Southwest, for example).

Greenhouse gas (GHG): Any of the atmospheric gases that absorbs longwave, or infrared, radiation that otherwise would pass from the Earth's surface through the atmosphere and into outer space. They include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (NO_2), and water vapor.

Magnitude of change: In climate models, the magnitude of change is how much the climate is projected to change over a given period of time. Climate scientists generally have more confidence in models' ability to project the *direction* of change, such as whether it will be hotter in the future; but not exactly how much hotter it will be.

Normals period: A reference period that is used to create standard climate statistics. A 30-year period was recommended by the World Meteorological Organization in the early 1900s as the minimum number of years to use in the calculation of climate averages. The current normal period is updated each decade to reflect the most recent 30 years. The current normal period is 1981–2010 and will be updated again in 2021 for the period of 1991–2020.

Pluvial: A period of time, often multiple years, in which a particular area experiences abundant or well-above average precipitation.

Representative Concentration Pathways (RCP): Scenarios of different levels of greenhouse gas emissions that are used to estimate future global temperatures. The four

RCPs used by the Intergovernmental Panel on Climate Change are 2.6, 4.5, 6.0, and 8.5; the numbers represent changes in radiative forcing, or the amount of outgoing infrared radiation relative to incoming shortwave solar radiation, at the top of the atmosphere.

Scenario: A description of a possible future state of the world. Scenarios do not represent what will happen; they represent what could happen, given our activities and choices.

Statistical downscaling: Correlating historical local and regional observations with data from global climate models to derive climate projections at local and regional scales.

Variability: A term to describe year-to-year changes in climatic conditions such as annual temperature and precipitation.

Weather: The day-to-day conditions in a particular area, such as temperature, precipitation, humidity, and wind.

Appendix A: Discussion of seasonal historical and projected climate data

Winter (December–February)

Between 1896 and 2017, the average temperature during winter (December–February) across Coconino County was 34.5° F (represented by the straight horizontal line in Figure A1). However, year-to-year the averages have ranged from below 26.9° F in 1933 to 39.5° F in 2015. Most winters since the mid-1980s have been above average. There have still been winters with below-average temperatures, however, these winters have been warmer than in previous years, with no years experiencing a winter with average temperatures colder than 32° F.

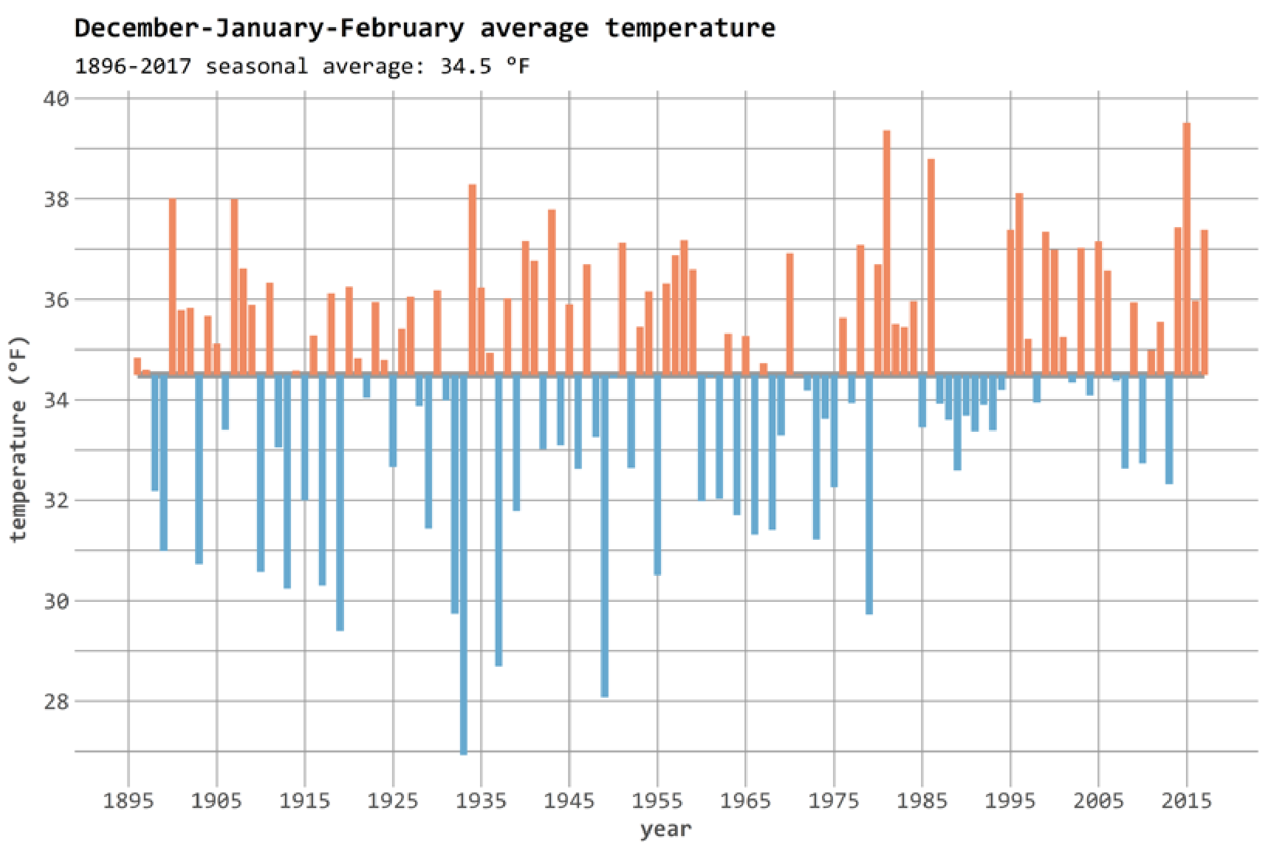

Figure A1: Average temperatures during December–February for Coconino County from 1896–2017.

In Figure A2, below, we see that minimum winter average temperatures (shown in yellow) for Coconino County have been rising faster than maximums (shown in red); rising minimum temperatures play a larger role in pushing average temperatures higher. We see the same trend with annual average temperatures (see Figure 7).

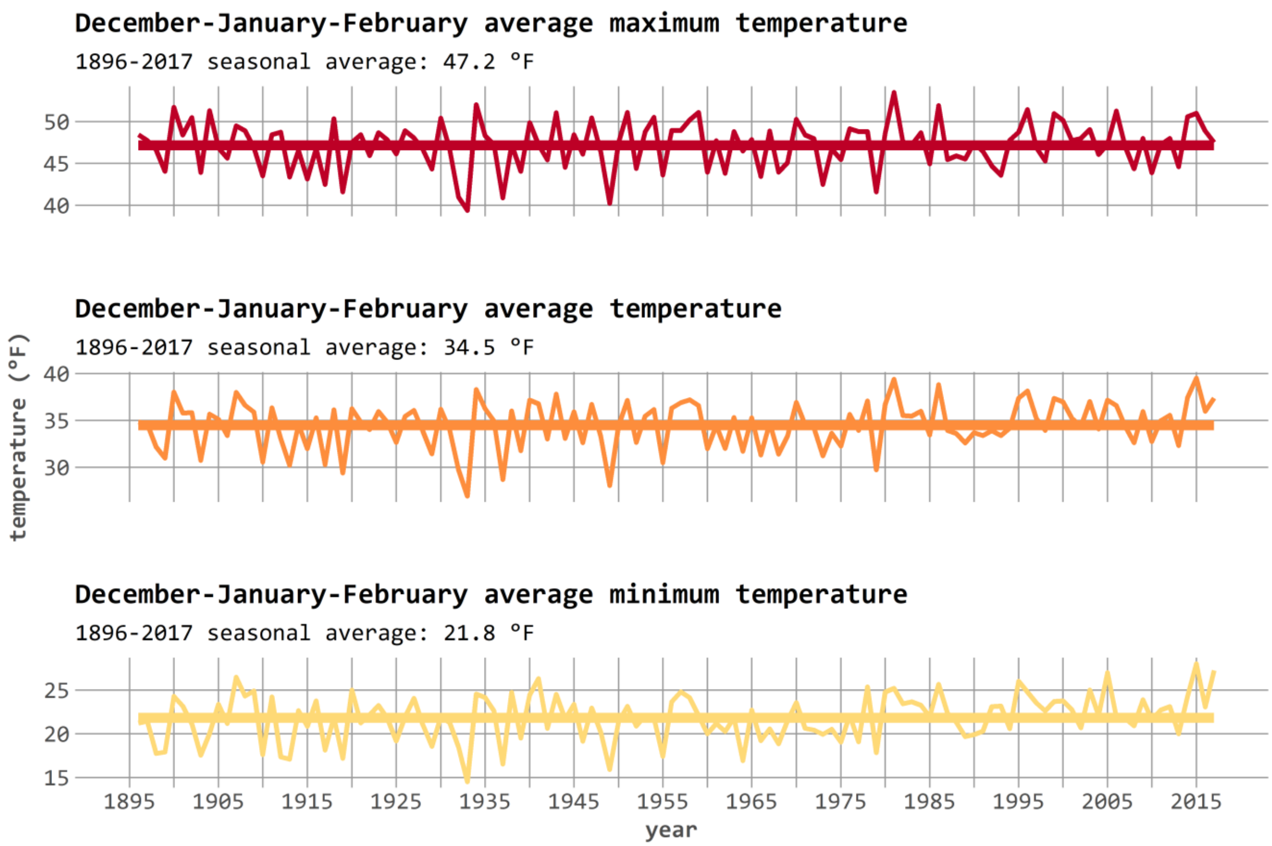

Figure A2: Average maximum (red), minimum (yellow), and overall average (orange) temperatures during December–February for Coconino County from 1896–2017.

Total winter precipitation averaged 3.8 inches for Coconino County from 1896–2017 (Figure A3) and ranged from 12.3 inches in 1993 to 0.49 inches in 2006. There is no discernible trend in amount of winter precipitation, just as there is no discernible trend in annual average precipitation (see Figure 9).

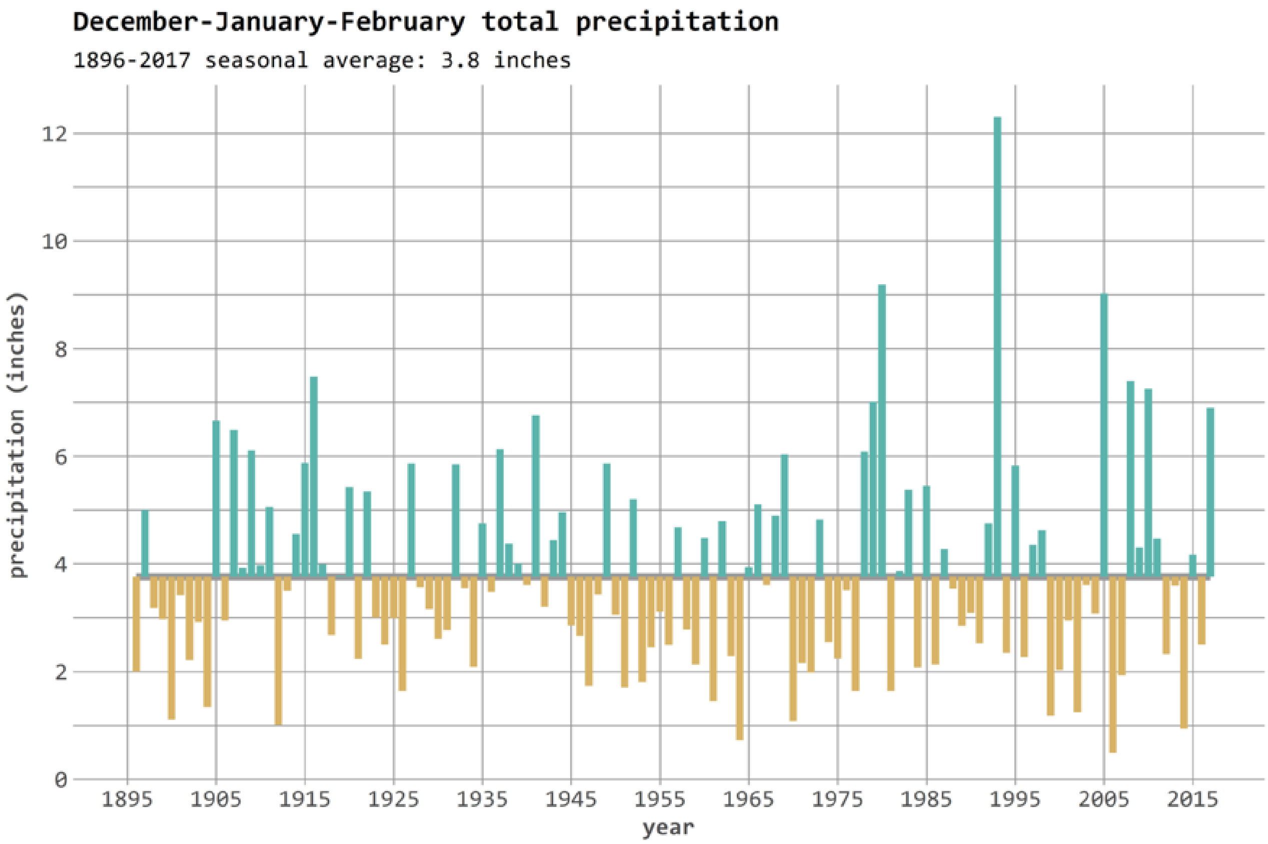

Figure A3: Total precipitation during December–February for Coconino County from 1896–2017.

Figure A4 shows projections of average temperature for December–February. Average winter temperatures are projected to rise by over 9° F above the long-term average of 34.5° F by 2100 under the higher scenario (RCP 8.5).

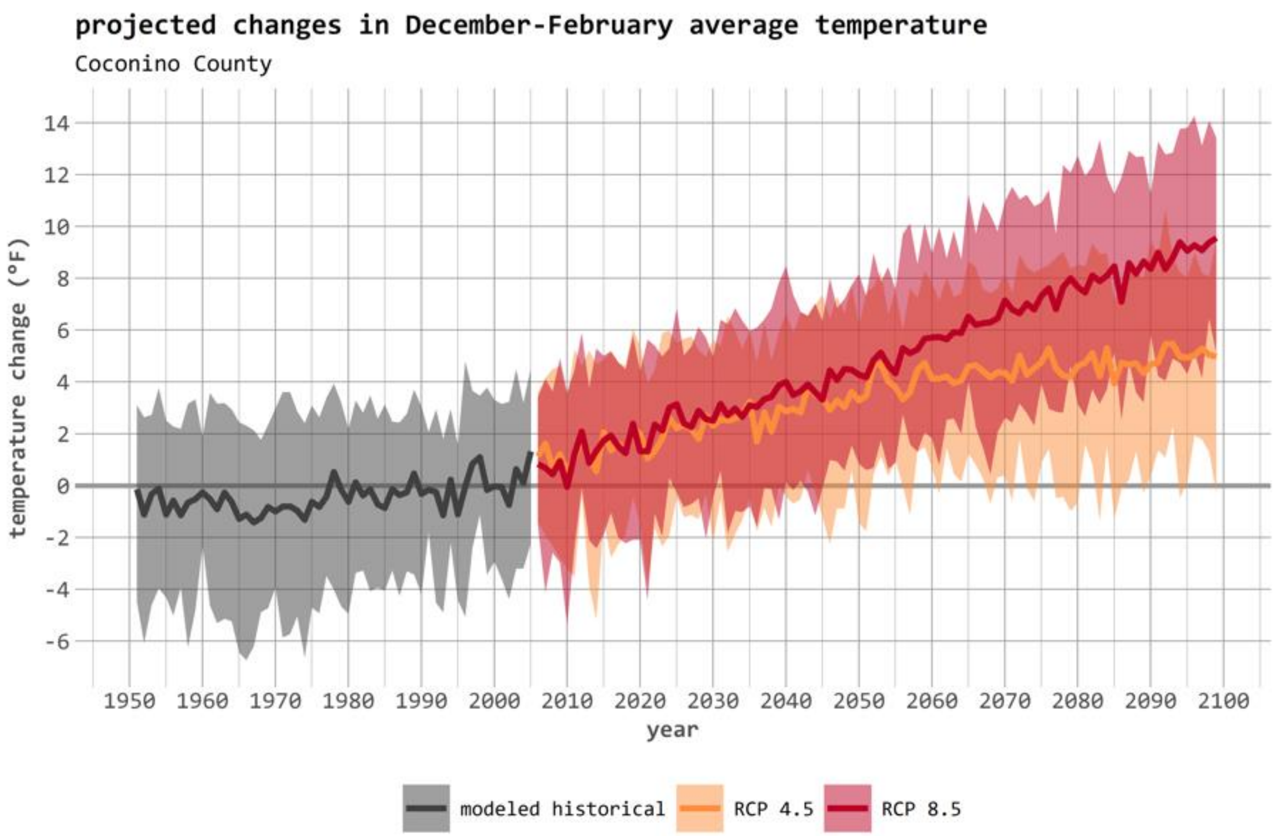

Figure A4: Downscaled model projections of average temperature for Coconino County during December–February.

Projections for precipitation show little to no change in average winter precipitation for Coconino County (Figure A5), just as with annual average precipitation. However, even with no change in precipitation, higher winter temperatures will result in more precipitation falling as rain than snow and will increase evaporation. These factors will likely lead to reduced snowpack and streamflows.

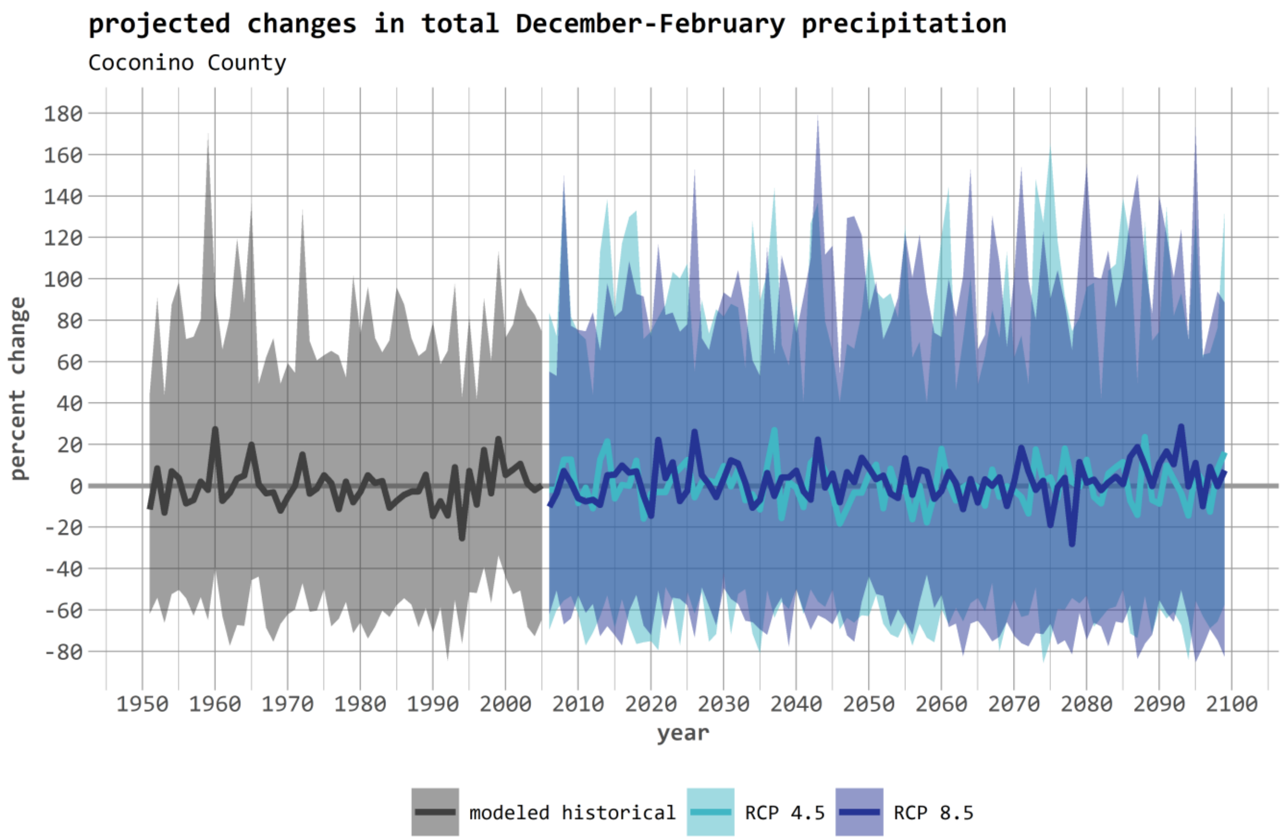

Figure A5: Downscaled projections of total precipitation for Coconino County during December–February.

Spring (March–May)

Between 1895 and 2017, the average temperature during spring (March–May) across Coconino County was 50.1° F (represented by the straight horizontal line in Figure A6). However, year-to-year the averages have ranged from below 45.1° F in 1917 to 55.9° F in 1934. Just like with annual average temperatures, spring temperatures have been mostly above average since the mid-1980s.

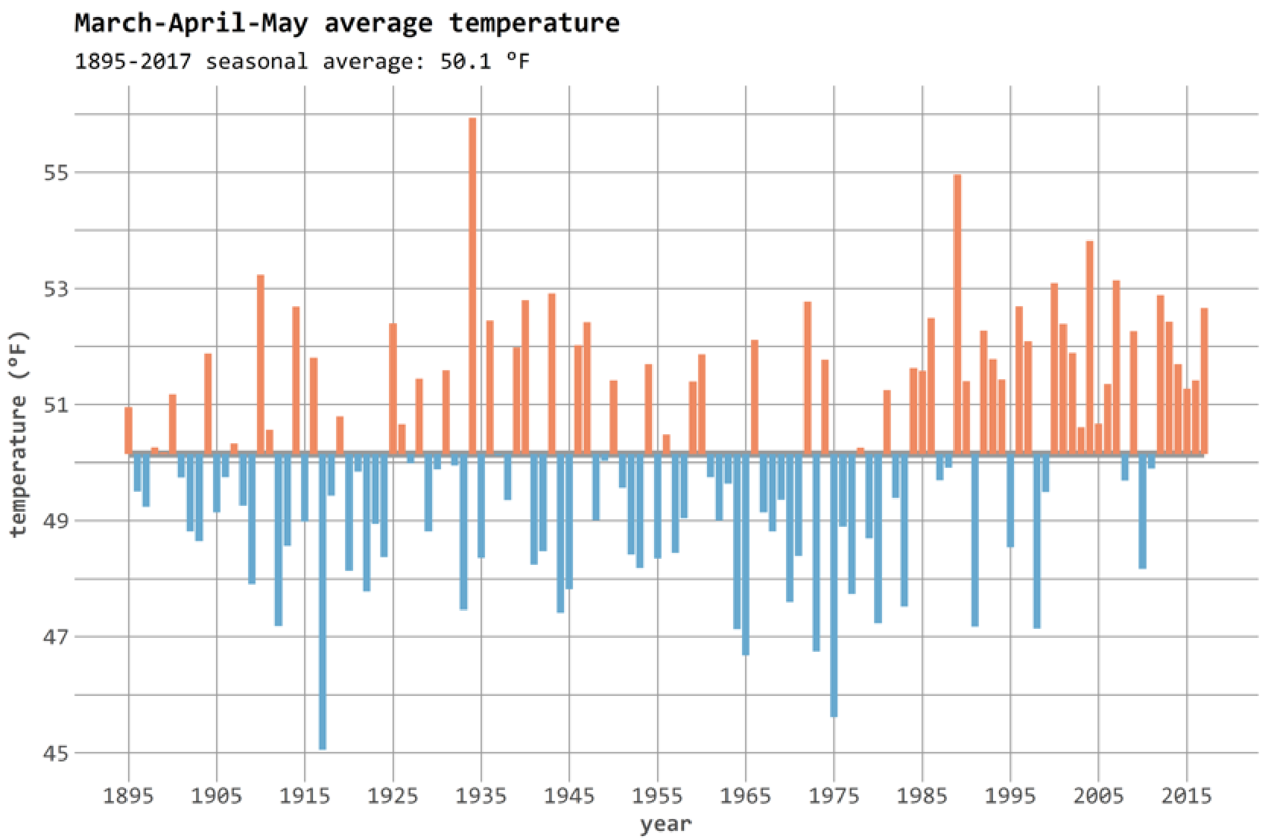

Figure A6: Average temperatures during March–May for Coconino County from 1895–2017.

Again, when looking at maximum and minimum temperatures (Figure A7), minimum spring temperatures more frequently been above the long-term average, similar to the trend seen in annual average temperatures and winter temperatures.

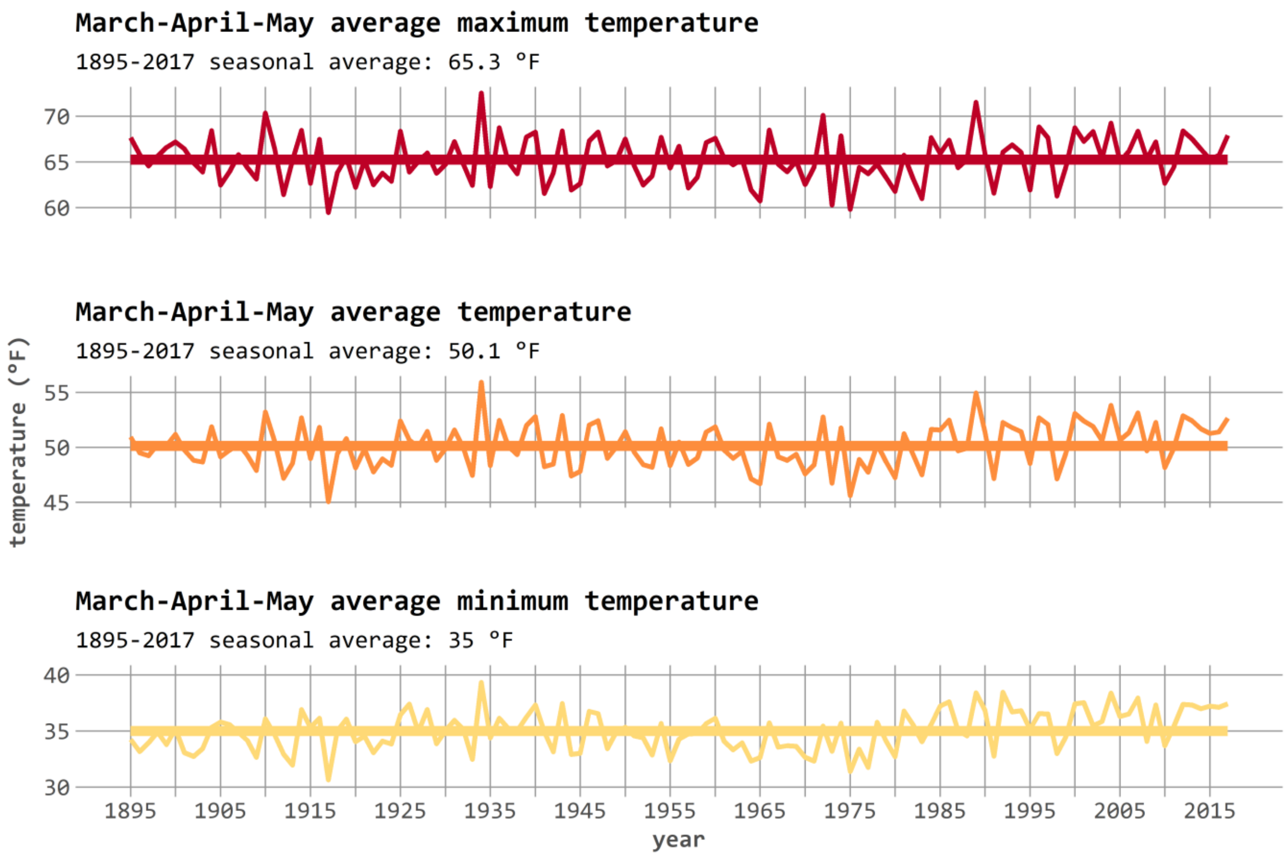

Figure A7: Average maximum (red), minimum (yellow), and overall average (orange) temperatures during March–May for Coconino County from 1895–2017.

Total spring precipitation averaged 2.6 inches for Coconino County from 1895–2017 (Figure A8), and ranged from 6.3 inches in 1941, to 0.4 inches in 1972. Since 2006, all but one year has been below average.

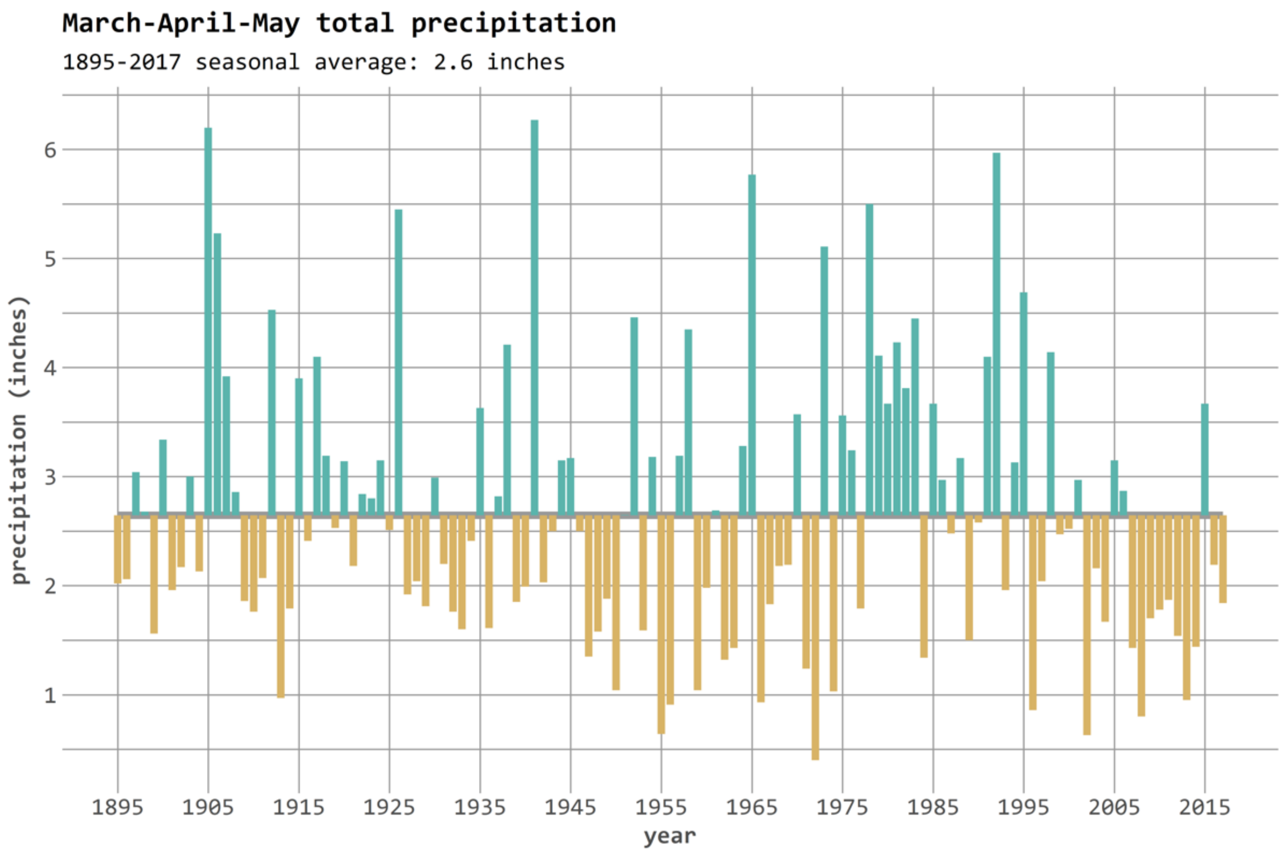

Figure A8: Total precipitation during March–May for Coconino County from 1895–2017.

Figure A9 shows temperature projections for Coconino County in spring. Temperatures are projected to increase by as much as 10° F above the long-term average of 50.1° F, similar to what is projected for annual average temperatures and winter temperatures.

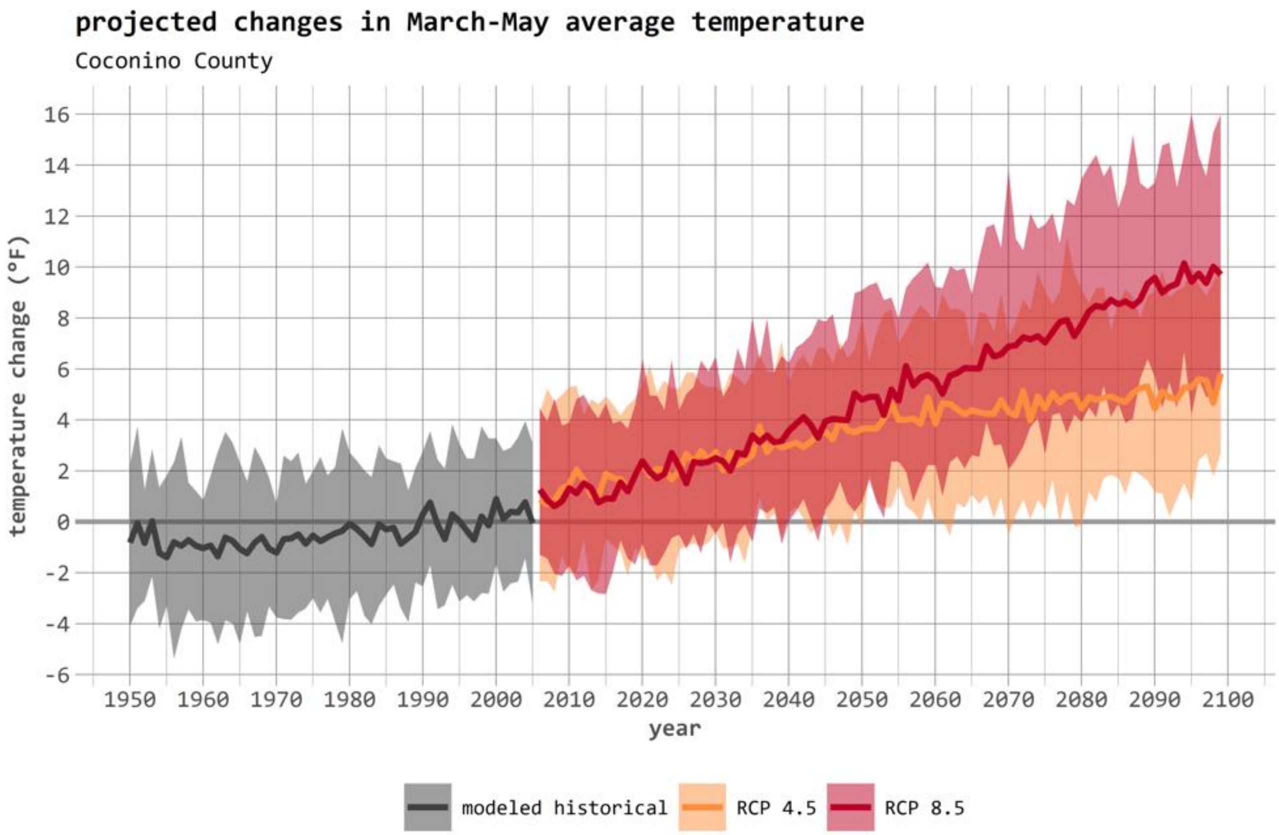

Figure A9: Downscaled model projections of average temperature for Coconino County during March–May.

Precipitation projections for spring, unlike those for winter and for annual average precipitation, appear to show a downward trend through 2100 (Figure A10). By 2100, the higher scenario (RCP 8.5) projects precipitation to be 20-40% below average for March–May. This projected change may reflect anticipated changes in the jet stream, which may move north and reduce the number of spring storms in our region (Easterling et al. 2017). However, confidence in projections of precipitation are not generally as strong as confidence in temperature projections because the climate models do not capture variables like the North American monsoon well, which contributes to less accuracy in the projections (Gershunov et al. 2013).

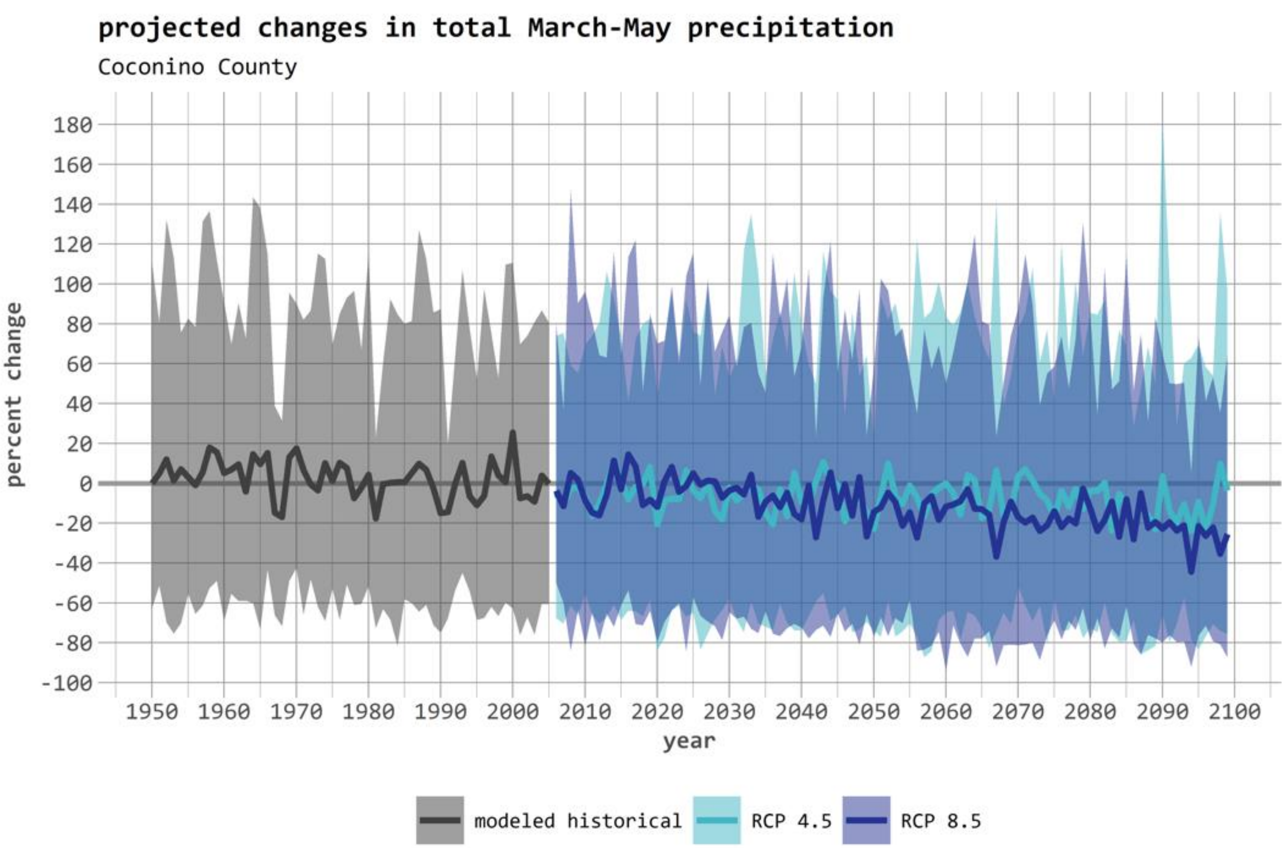

Figure A10: Downscaled projections of total precipitation for Coconino County during March–May.

Summer (June–August)

Between 1895 and 2017, the average temperature during summer (June–August) across Coconino County was 70.9° F (represented by the straight horizontal line in Figure A11). Year-to-year averages have ranged from below 68.0° F in 1965 to 74.3° F in 2002. **Since the year 2000, *all* years have experienced at or above-average temperatures**.

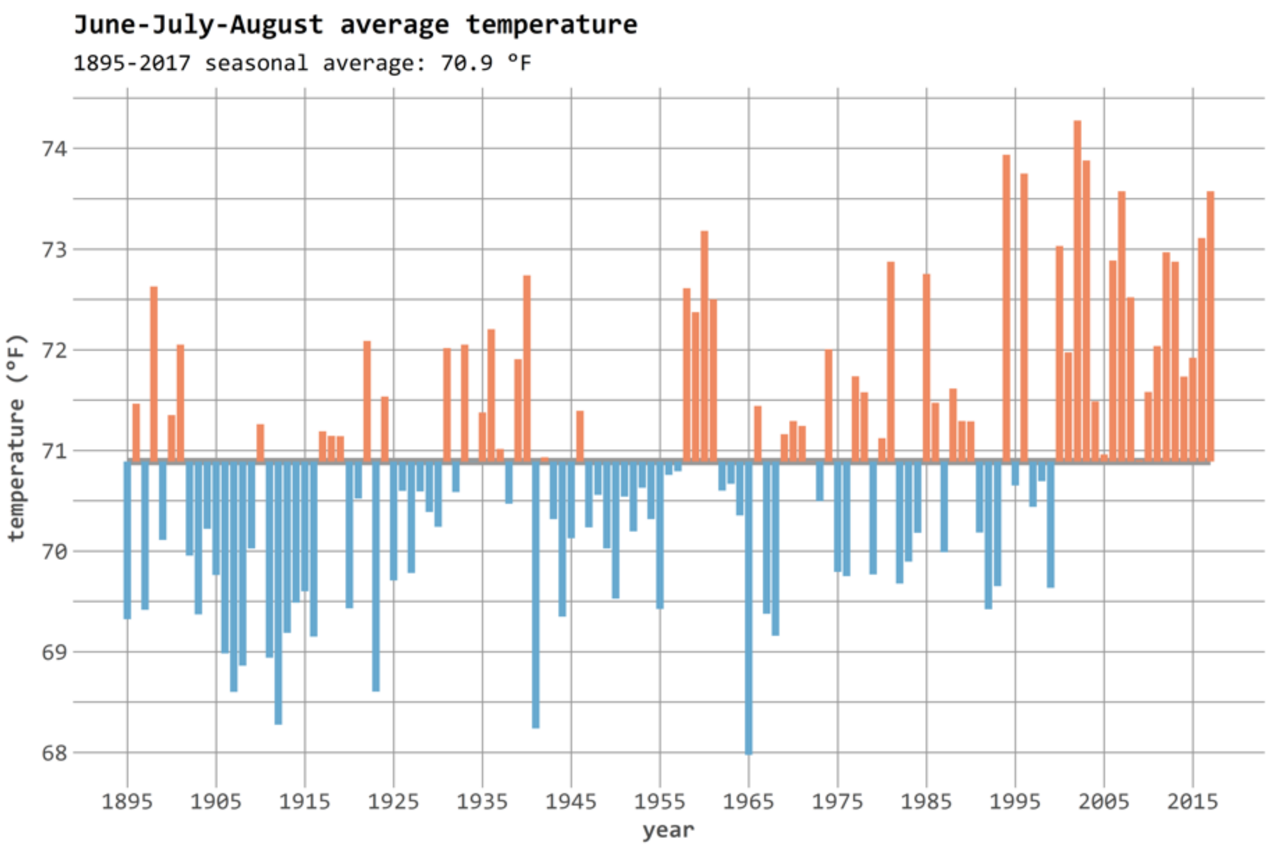

Figure A11: Average temperatures during June–August for Coconino County from 1895–2017.

Figure A12 shows maximum, minimum, and average summer temperatures. As observed in other seasons, minimum temperatures during the summer have been above average more frequently, which is driving average temperatures higher.

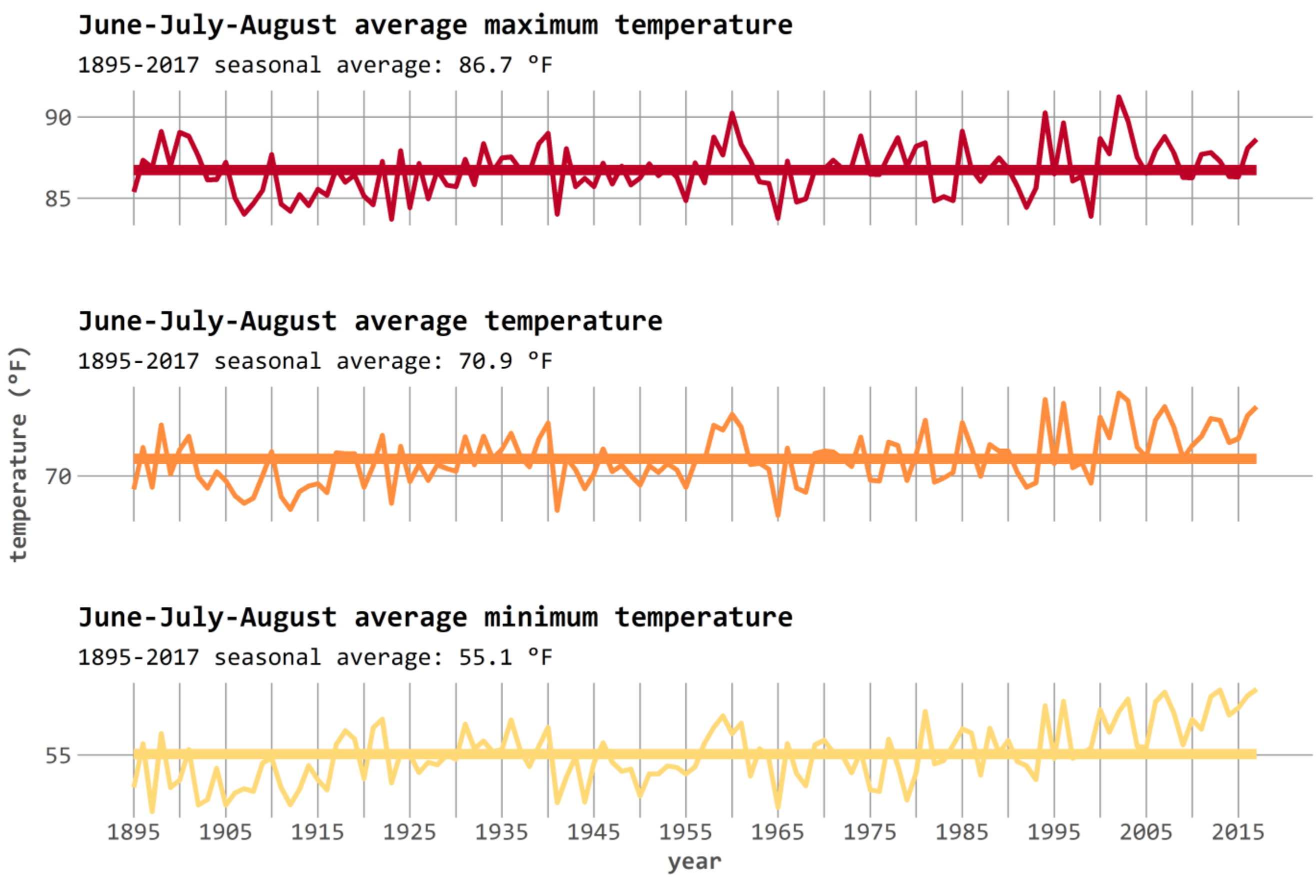

Figure A12: Average maximum (red), minimum (yellow), and overall average (orange) temperatures during June–August for Coconino County from 1895–2017.

Total summer precipitation averaged 4 inches for Coconino County from 1895–2017, and ranged from 7.2 inches in 1921, to 1.3 inches in 1900 (Figure A13). There has been no observed trend in summer precipitation. However, as stated previously, there will be more evaporation as temperatures rise, reducing streamflows and decreasing soil moisture.

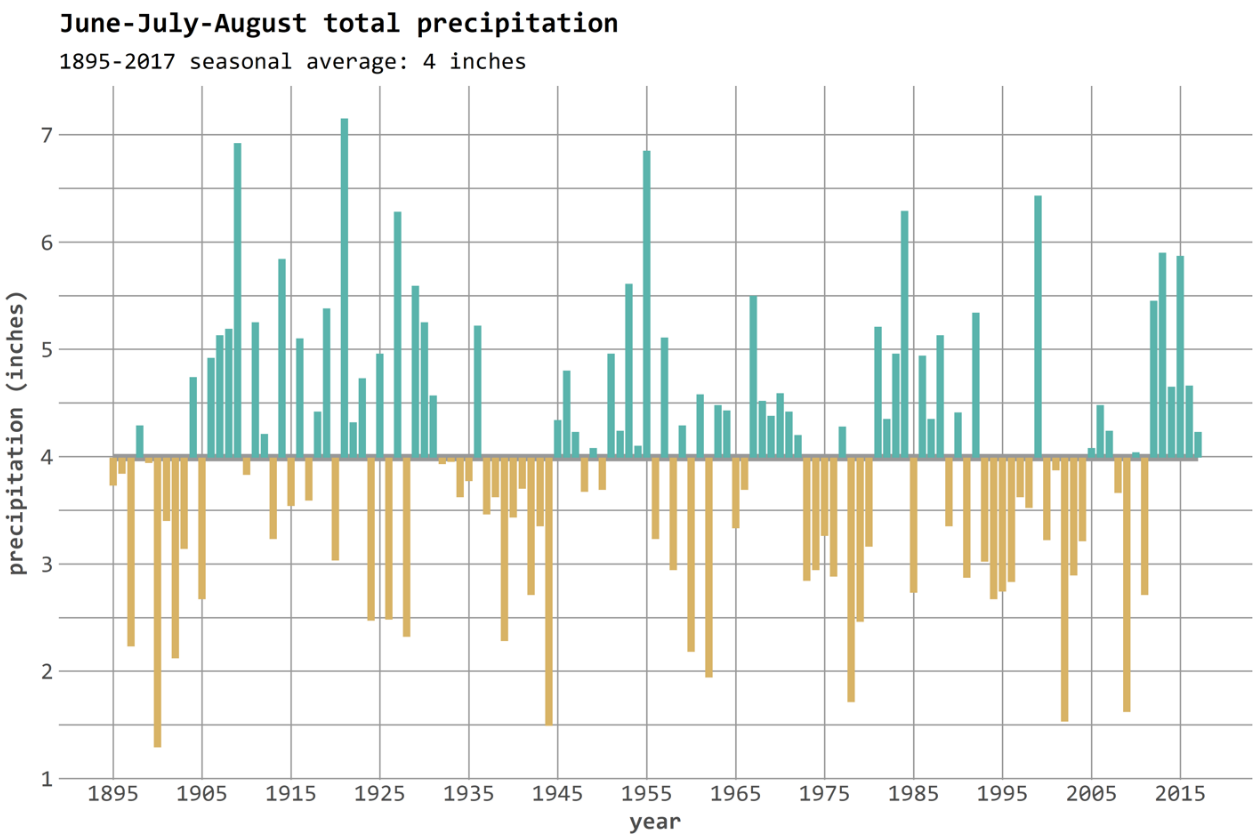

Figure A13: Total precipitation during June–August for Coconino County from 1895–2017.

Temperatures are projected to rise more in the summer than in winter or spring, with temperatures projected to rise by almost 12° F by 2100, based on the higher scenario (RCP 8.5) (Figure A14).

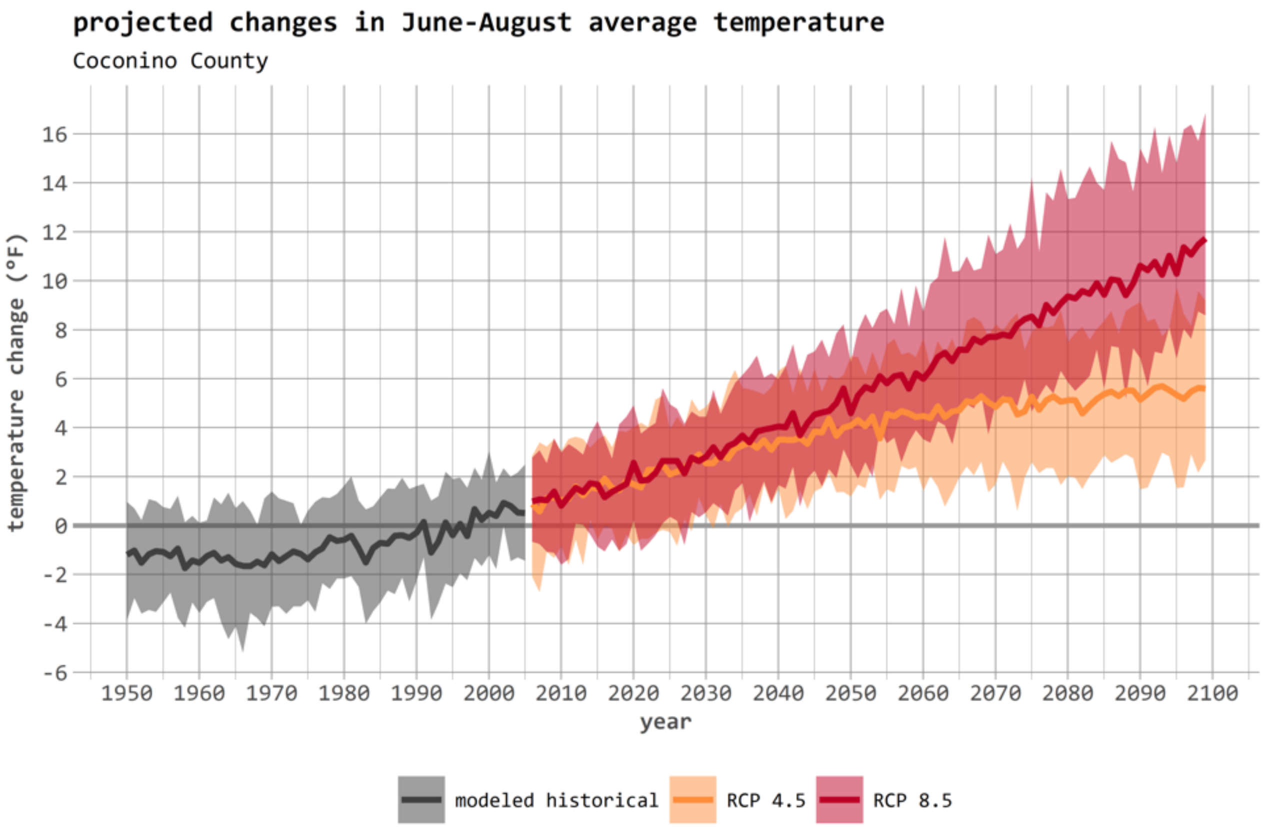

Figure A14: Downscaled model projections of average temperature for Coconino County during June–August.

Figure A15 shows projected precipitation for Coconino County during summer. As with historical observations we see no trend towards wetter or drier conditions in future summer precipitation. However, changes in character and timing of extreme precipitation events are possible due to rising temperatures (Gershunov et al. 2013; Castro et al. 2017).

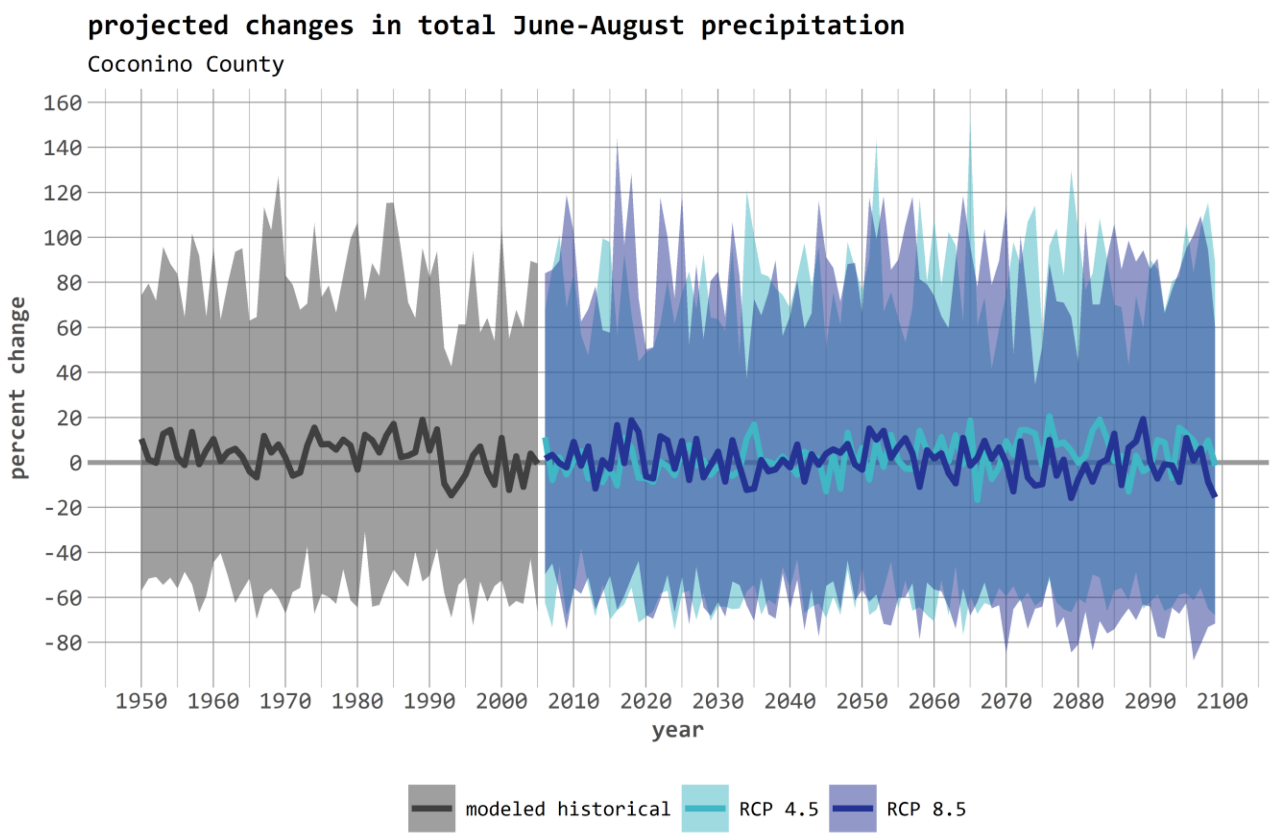

Figure A15: Downscaled projections of total precipitation for Coconino County during June–August.

Fall (September–November)

Between 1895 and 2017, the average temperature during fall (September–November) across Coconino County was 53.5° F (represented by the straight horizontal line in Figure A16). Year-to-year the averages have ranged from 50.4° F in 1912 to 56.9° F in 2017. Since the mid-1980s, most years have experienced above-average temperatures. **2017 was the warmest *year* on record for Coconino County, and after breaking the year into seasons we can see that exceptionally high fall temperatures played a large role in the annual record.**

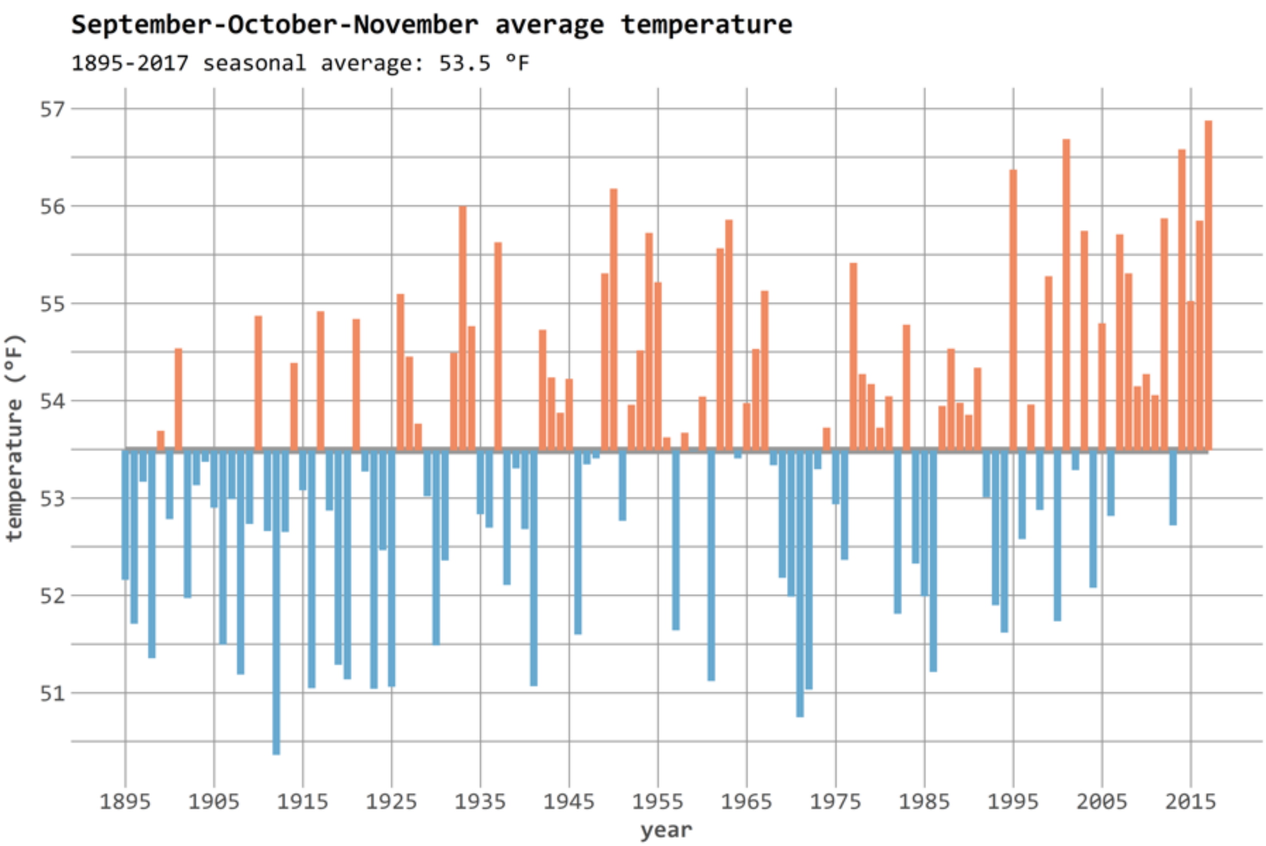

Figure A16: Average temperatures during September–November for Coconino County from 1895–2017.

Figure A17 shows maximum, minimum, and average fall temperatures. As observed in other seasons, minimum temperatures during the fall have been driving the trend of higher average temperatures.

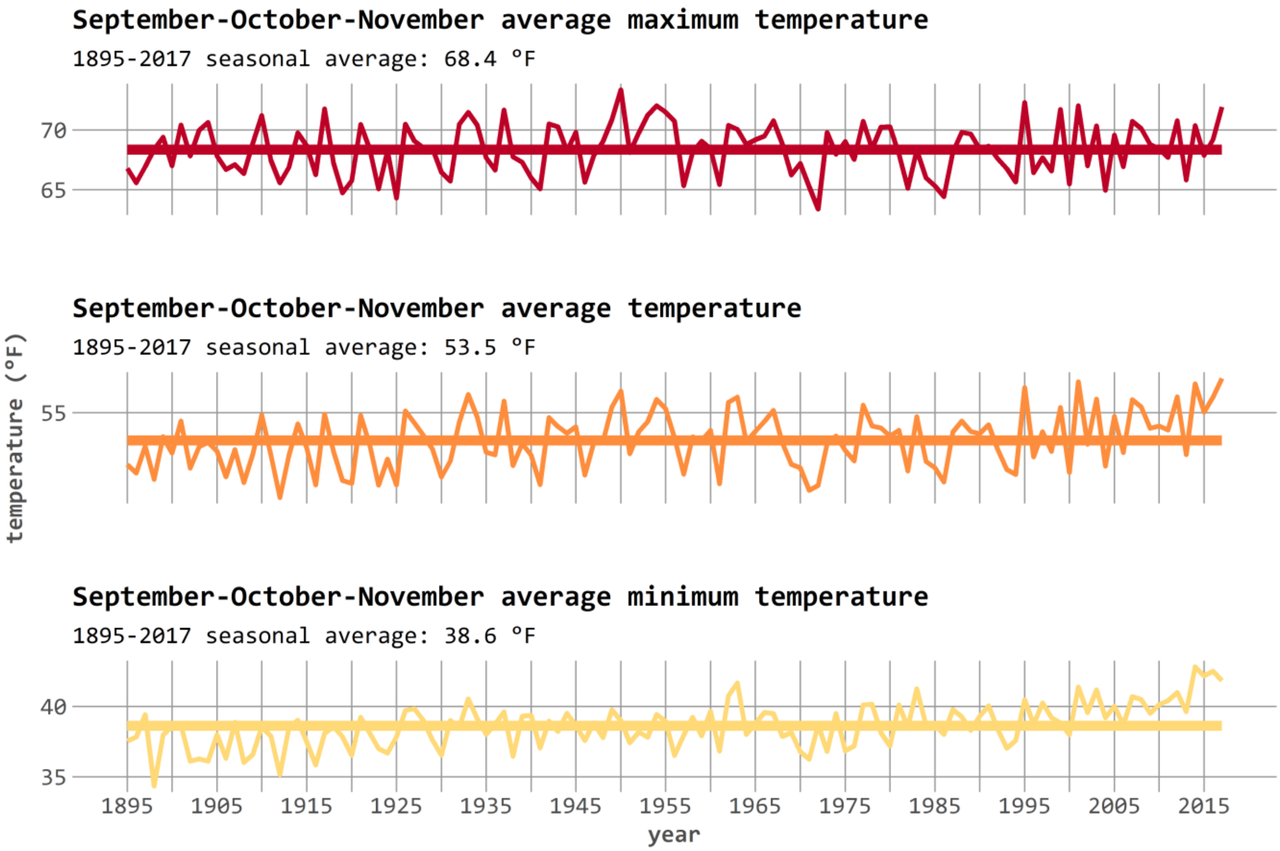

Figure A17: Average maximum (red), minimum (yellow), and overall average (orange) temperatures during September–November for Coconino County from 1895–2017.

Similar to winter and summer, there has been no observed trend in total fall precipitation (Figure A18) Fall precipitation has averaged 3.3 inches for Coconino County from 1895–2017 and has ranged from 8.8 inches in 1972 to 0.7 inches in 1956.

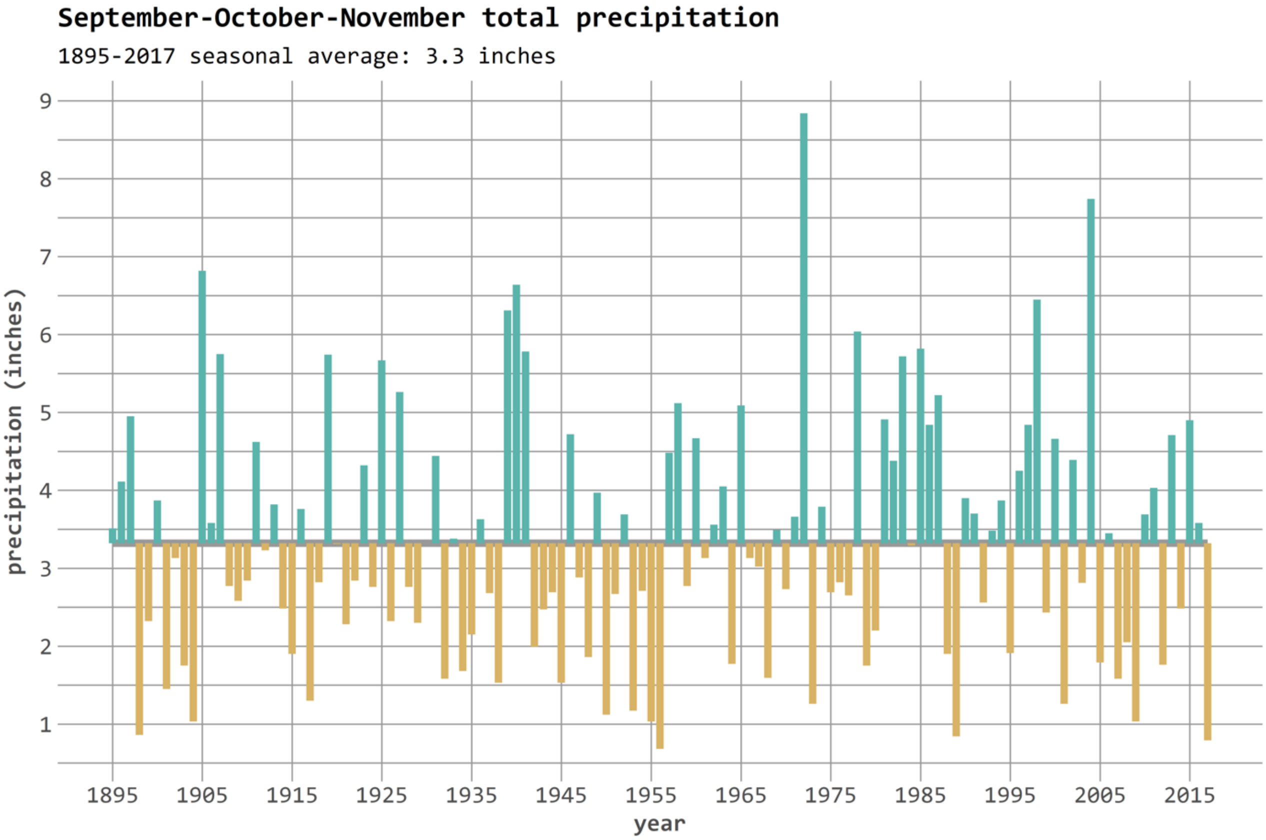

Figure A18: Total precipitation during September–November for Coconino County from 1895–2017.

Projections of future temperatures in fall are similar to those of summer, with models showing a 12° F increase in temperatures by 2100 based on the higher emissions scenario (RCP 8.5) (Figure A19). This is higher than what models are projecting for winter and spring. Model projections of precipitation again show little to no trend for fall months (Figure A20).

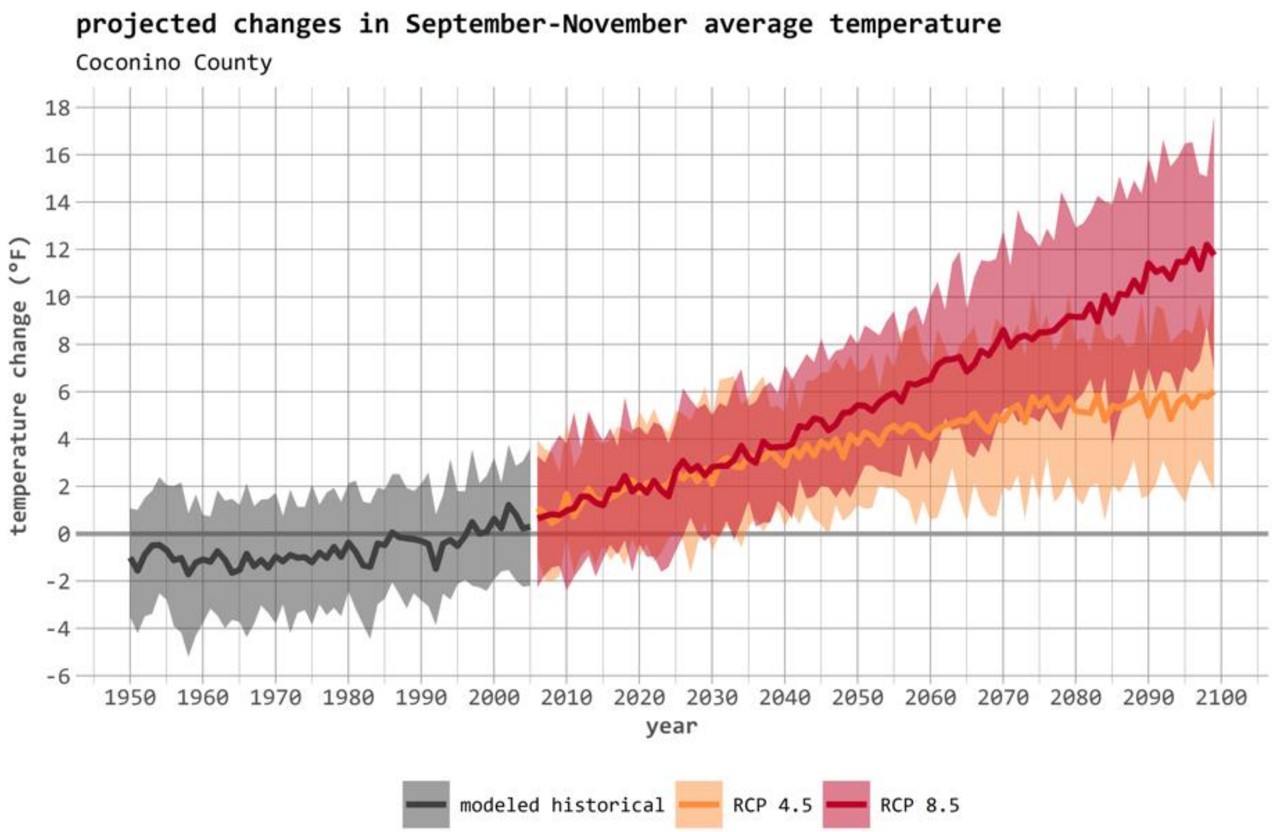

Figure A19: Downscaled model projections of average temperature for Coconino County during September–November.

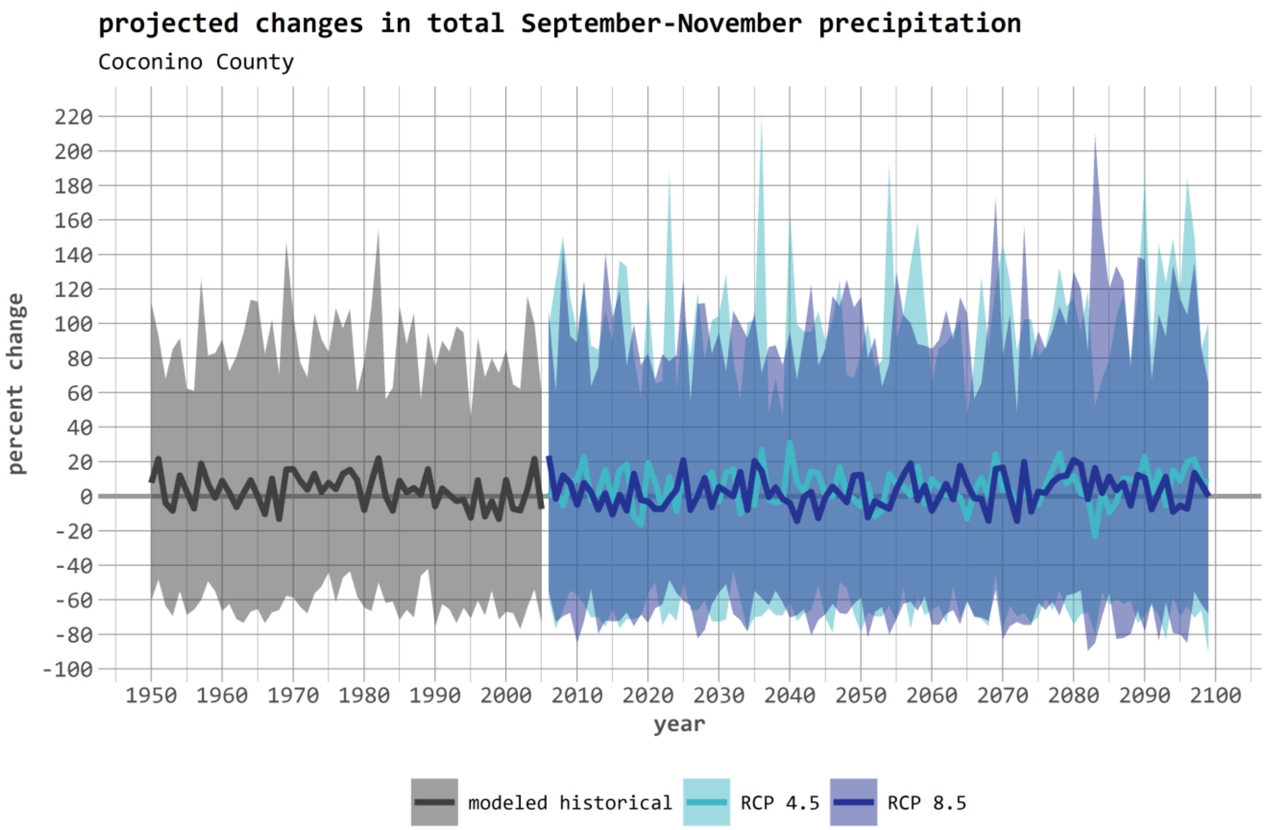

Figure A20: Downscaled projections of total precipitation for Coconino County during September–November.

References Cited

Castro, C. L. 2017. Assessing Climate Change Impacts for DoD Installations in the Southwest United States During the Warm Season. Prepared for the Department of Defense, Strategic Environmental Research and Development Program. 113pp.

Daly, C., W.P. Gibson, G.H. Taylor, G.L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research* 22:99-113.

Easterling, D.R., K.E. Kunkel, J.R. Arnold, T. Knutson, A.N. LeGrande, L.R. Leung, R.S. Vose, D.E. Waliser, and M.F. Wehner. 2017. Precipitation change in the United States. In *Climate Science Special Report: Fourth National Climate Assessment, Volume I*, edited by D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart and T. K. Maycock. Washington, DC: U.S. Global Change Research Program.

Executive Office of the President. 2013. The President's Climate Action Plan. In *Executive Order 13514*.

Gershunov, Alexander, Balaji Rajagopalan, Jonathan Overpeck, Kristen Guirguis, D.R. Cayan, Mimi Hughes, Michael D. Dettinger, Chris Castro, Rachel E. Schwartz, Michael Anderson, Andrea J. Ray, Joe Barsugli, Tereza Cavazos, and Michael Alexander. 2013. Future Climate: Projected Extremes. In *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate Assessment*, edited by G. Garfin, A. Jardine, R. Merideth, M. Black and S. LeRoy. Washington D.C.: Island Press.

Kennedy, Caitlyn. 2014. Does "global warming" mean it's warming everywhere? *ClimateWatch Magazine*.

Lahmers, T.M., C.L. Castro, D.K. Adams, Y.L. Serra, J.J. Brost, and T. Luong. 2016. Long-Term Changes in the Climatology of Transient Inverted Troughs over the North American Monsoon Region and Their Effects on Precipitation. *Journal of Climate* 29:6037-6064.

Leibensperger, E. M., L. J. Mickley, D. J. Jacob, W. T. Chen, J. H. Seinfeld, A. Nenes, P. J. Adams, D. G. Streets, N. Kumar, and D. Rind. 2012. Climatic effects of 1950 - 2050 changes in US anthropogenic aerosols; Part 2: Climate response. *Atmos. Chem. Phys.* 12 (7):3349-3362.

Luong, TM, CL Castro, HI Chang, T Lahmers , DK Adams, and CA Ochoa-Moya. 2017. The More Extreme Nature of North American Monsoon Precipitation in the Southwestern United States as Revealed by a Historical Climatology of Simulated

Severe Weather Events. *Journal of Applied Meteorology and Climatology* 56:2509 - 2529.

Meehl, Gerald A., Julie M. Arblaster, and Christine T. Y. Chung. 2015. Disappearance of the southeast U.S. “warming hole” with the late 1990s transition of the Interdecadal Pacific Oscillation. *Geophysical Research Letters* 42 (13):5564-5570.

Melillo, Jerry, Terese C. Richmond, and G.W. Yohe, eds. 2014. *Climate change consequences in the United States: The third national climate assessment.*: U.S. Global Change Research Program.

Moser, Susanne, and J.A. Eckstrom. 2010. A framework to diagnose barriers to climate change adaptation. *PNAS* 107 (51):22026-22031.

Overpeck, Jonathan, Gregg Garfin, Angela Jardine, Dave Busch, Dan Cayan, Michael D. Dettinger, Erica Fleishman, Alexander Gershunov, Glen MacDonald, Kelly T. Redmond, William Travis, and Bradley Udall. 2013. Summary for Decision Makers. In *Assessment of Climate Change in the Southwest*, edited by G. Garfin, A. Jardine, R. Merideth, M. Black and J. Overpeck: Island Press.

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, B. DeAngelo, S. Doherty, K. Hayhoe, R. Horton, J.P. Kossin, P.C. Taylor, A.M. Waple, and C.P. Weaver. 2017. Executive summary. In *Climate Science Special Report: Fourth National Climate Assessment, Volume I* edited by D. J. Wuebbles, D. W. Fahey, K. A. Hibbard, D. J. Dokken, B. C. Stewart and T. K. Maycock. Washington, DC.